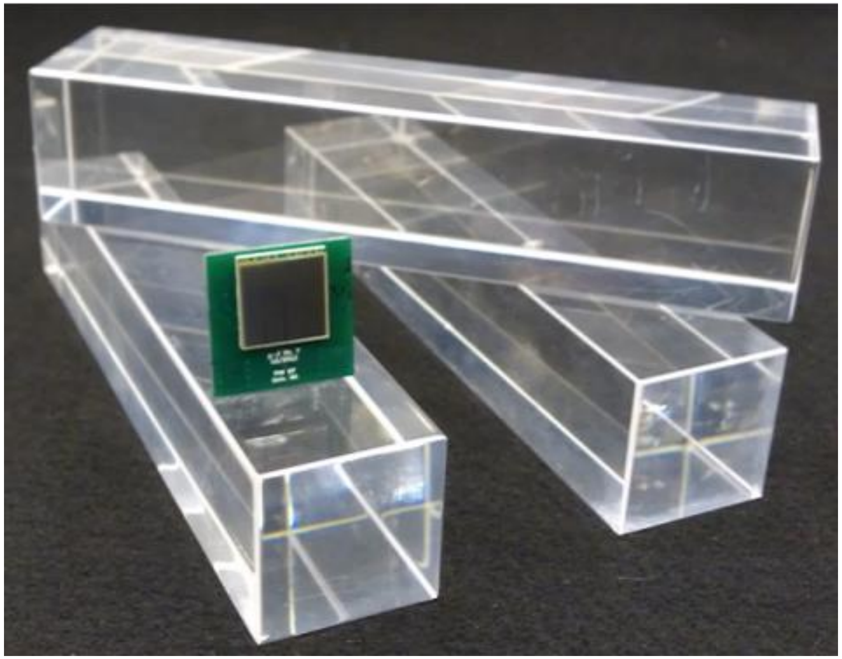
Detector R&D for g-2

David Hertzog*
University of Washington

- **Context: The new Muon g-2 Experiment**
  - **What you need to know**
- **Lead Fluoride Crystals**
- **Silicon Photo-Multipliers**
- **SLAC Test Beam**

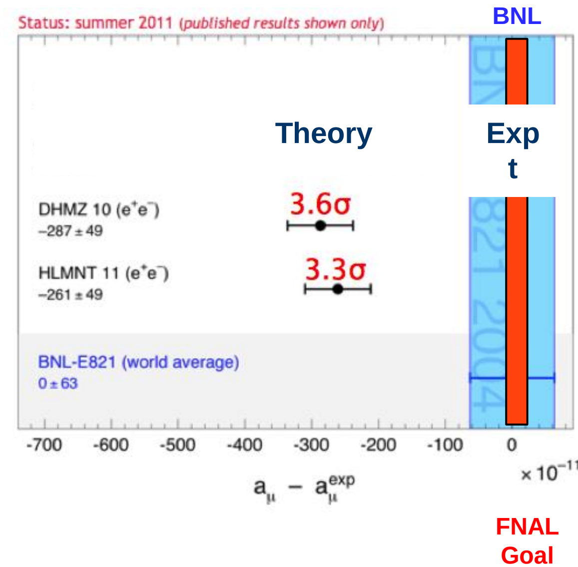


***Team: UW group: P. Alonzi, A. Fienberg, P. Kammel, J. Kaspar, M. Smith, T. VanWechel, K. Wall, B. Kiburg (now FNAL); P. Winter (now ANL); and K. Yai (Osaka);**

CONTEXT

Some things you need to know to follow this talk better

The statistically limited g-2 measurement is 3.6σ from the Standard Model. Now what?

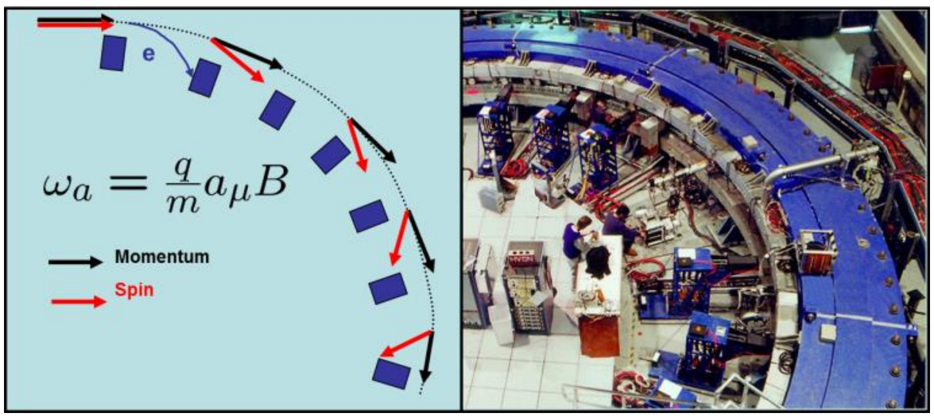


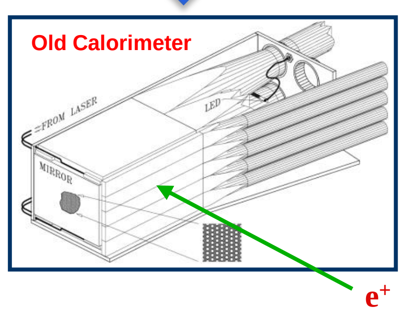
"Do the measurement better …"

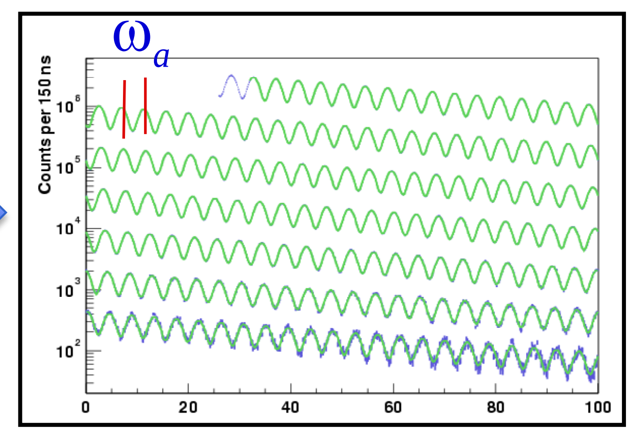
need More Muons

need Reduced Systematics

Implications for detectors

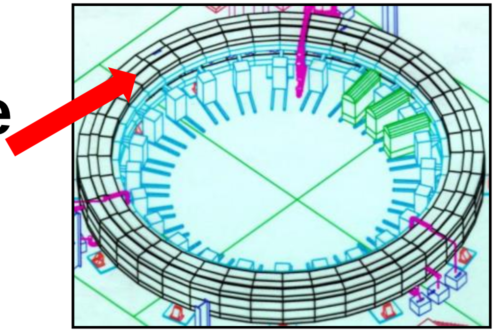




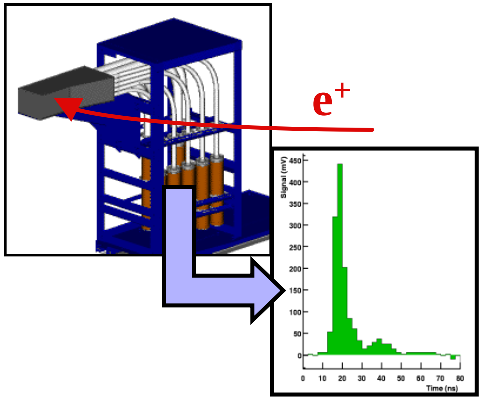


E989 completed CD-1; 38 Institutions, > 150 members; Start end of 2016

How is data obtained?



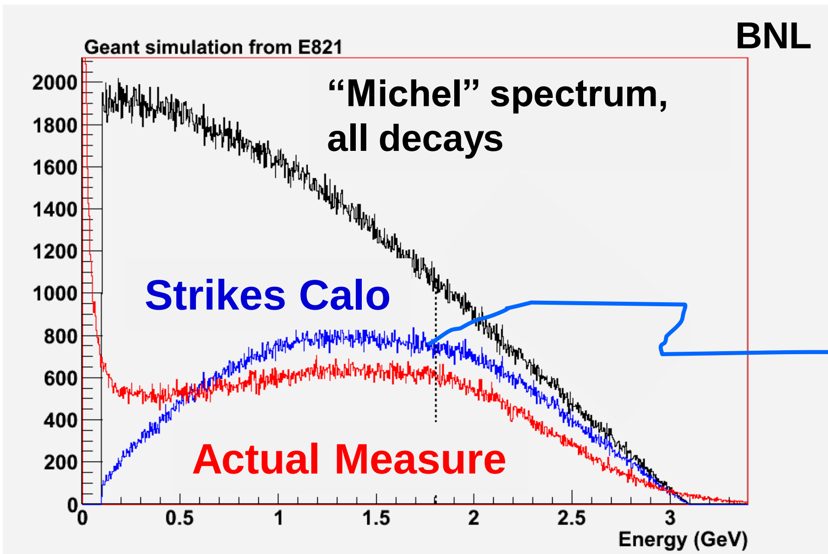
1. Bunch of μ^+ (up to 10,000) injected into the storage ring
   - Muon lifetime: $\gamma\tau = 64\ \mu s$
   - Decay e^+ range: <u>0 – 3.1 GeV</u>
   - Strike one of the 24 calorimeters
2. Observe events for ~700 μs
   - Record continuous waveforms
     - 12-bit resolution @ 500 MHz
     - 1296 channels → 680 MB per fill
   - Transfer, sort, pulse-find, pre-analyze during time between fills

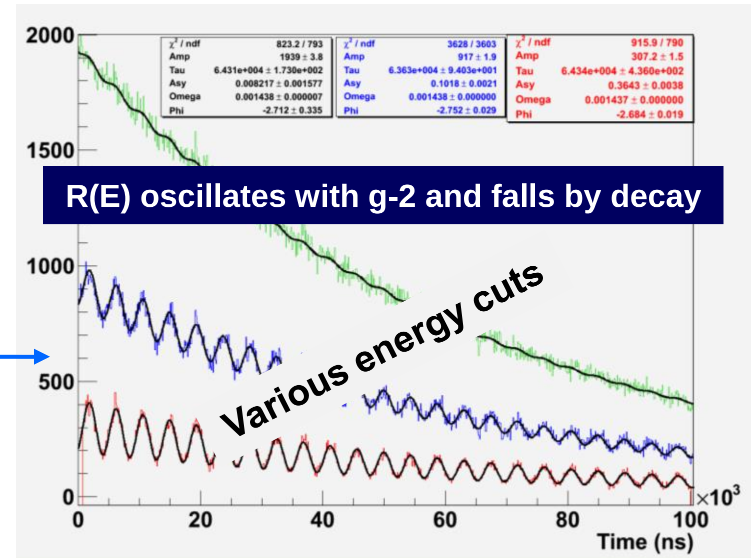


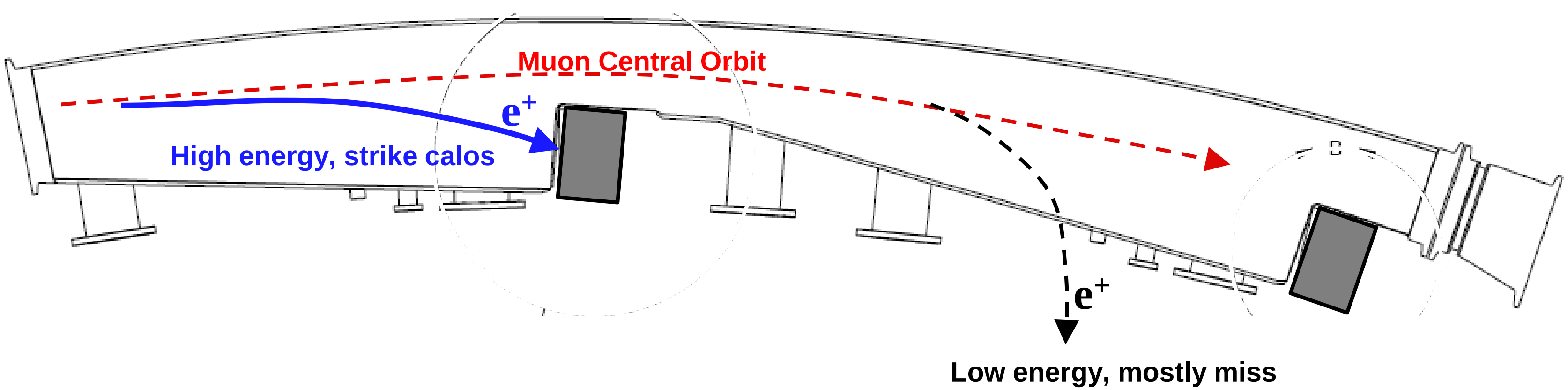
- Repeat sequence at 12 Hz
  - 8.1 GB/s transferred to GPU farm*
- Run continuously for more than a year
- Vary conditions for systematics

*not counting calibration, straw chambers, etc.

24 “finite” detector stations define acceptance





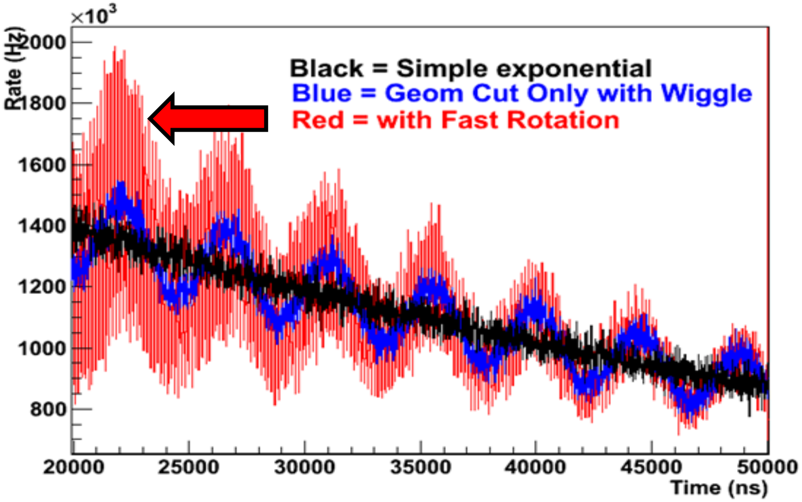


What you "want" is different from what you get

- **Desire: Electrons with <u>E > 1.8 GeV</u> (12%)**
- **You get: Everything that hits detectors**
  - **Modulated by g-2: 4.3 μs period; Amp is *A(E)***
  - **Modulated by Fast Rotation of incoming beam bunch**

High rate exacerbates pileup & gain stability issues

149 ns cyclotron frequency exaggerates actual rate on detectors



Pileup scales at $\langle R_{wiggle+FR} \rangle^2 \Delta t$, where Δt is the resolving time). For Δt = 6 ns, we can expect an unresolved pileup fraction after 30 μs when physics fit starts of ~0.9%

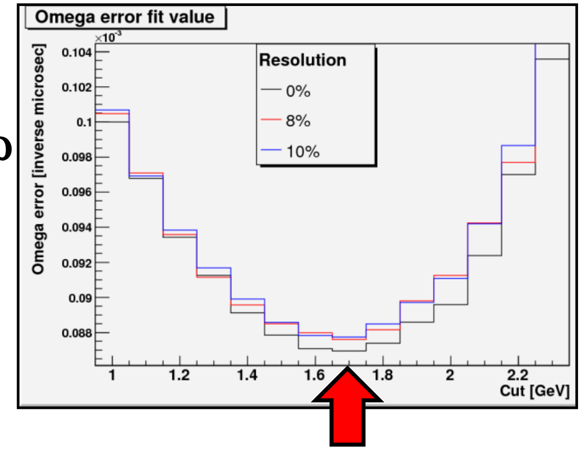
>2 MHz per calo minimal

Note: Rates are estimated, but could be much higher as FNAL is working on injection efficiency improvements.

What drives the detector choice?

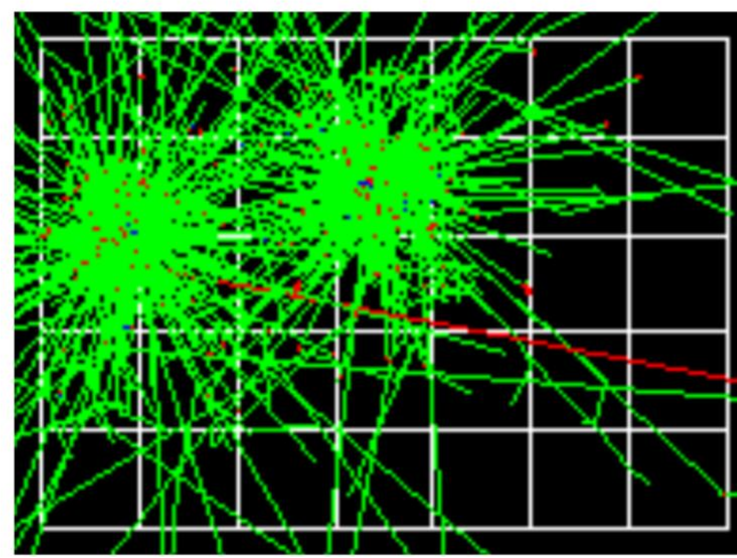
- **Compact** based on fixed space
- **Non-magnetic** to avoid field perturbations
- **Resolution** not too critical for $\delta\omega_a$
  - Useful for pileup, gain monitoring, shower partitioning and low thresholds
- **Gain stability** depends on electronics and calibration system
- **Pileup** depends on signal speed and shower separation
  - Subdivide calorimeter

$\delta\omega/\omega$

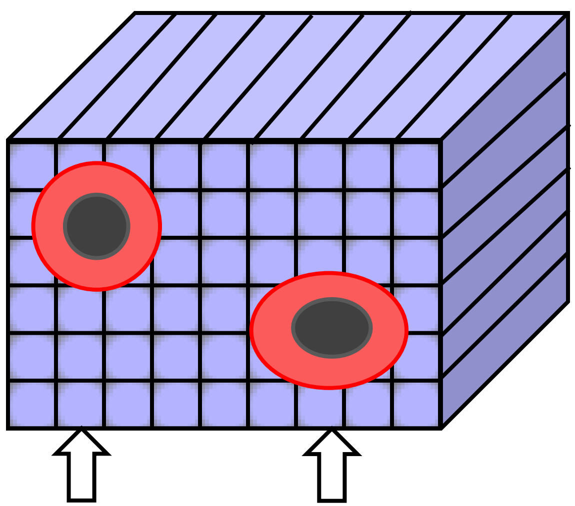


For 1.6 GeV cut, resolution hardly matters for best $\delta\omega/\omega$

Double Shot (rear view)



1 Moliere R
2 Moliere R



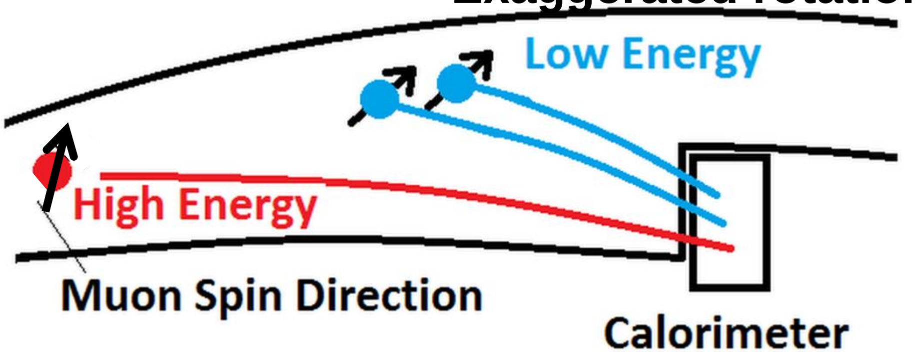
Head on (high E)

High angle (low E)

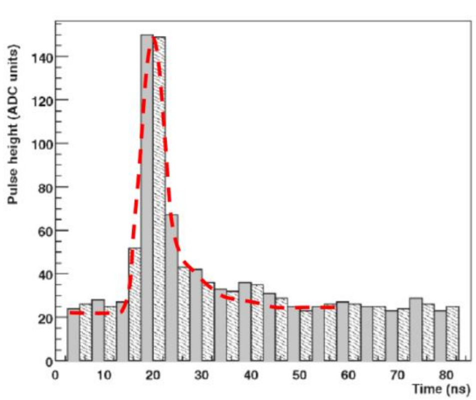
Pileup for g-2 is special

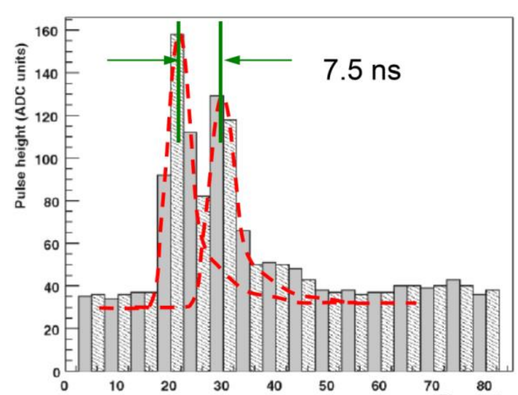
- 2 low-energy electrons can look like 1 (good) high-energy electron
- Avg. spin direction of Blue *ahead* of Red
- Probability of these has $e^{-2t/\tau}$ dependence
  - → early to late change systematic

Exaggerated rotation



- Waveform digitization: essential
- Fast pulses: essential
- Controllable tails: essential





We can separate down to about 5 ns

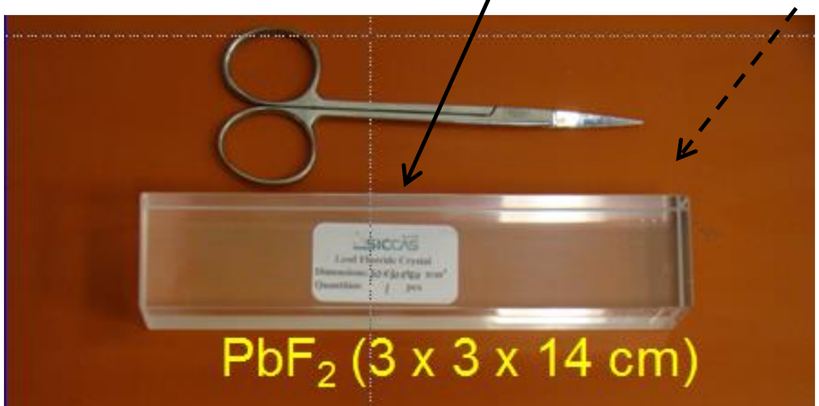
Choice of Calorimeter

We considered these three materials:

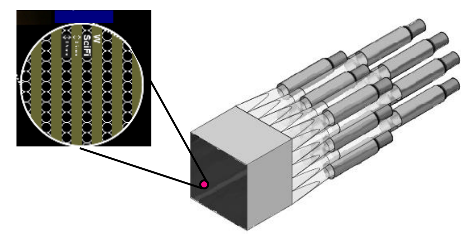
All are dense and non-magnetic and relatively “fast”

Material	PbF2	PbWO4 (undoped)	W / SciFi
Type	Cerenkov crystal	Cerenkov & Scintillation crystal	Sampling / scintillating fibers
Radiation length	0.93 cm	0.89 cm	0.69 cm
Moliere radius	1.8 cm (Cerenkov)	2.0 cm	1.73 cm
Typical resolution @ 2 GeV	< 3 %	2 %	10 %

similar



PbF_2 (3 x 3 x 14 cm)

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A tungsten/scintillating fiber electromagnetic calorimeter prototype for a high-rate muon (g – 2) experiment

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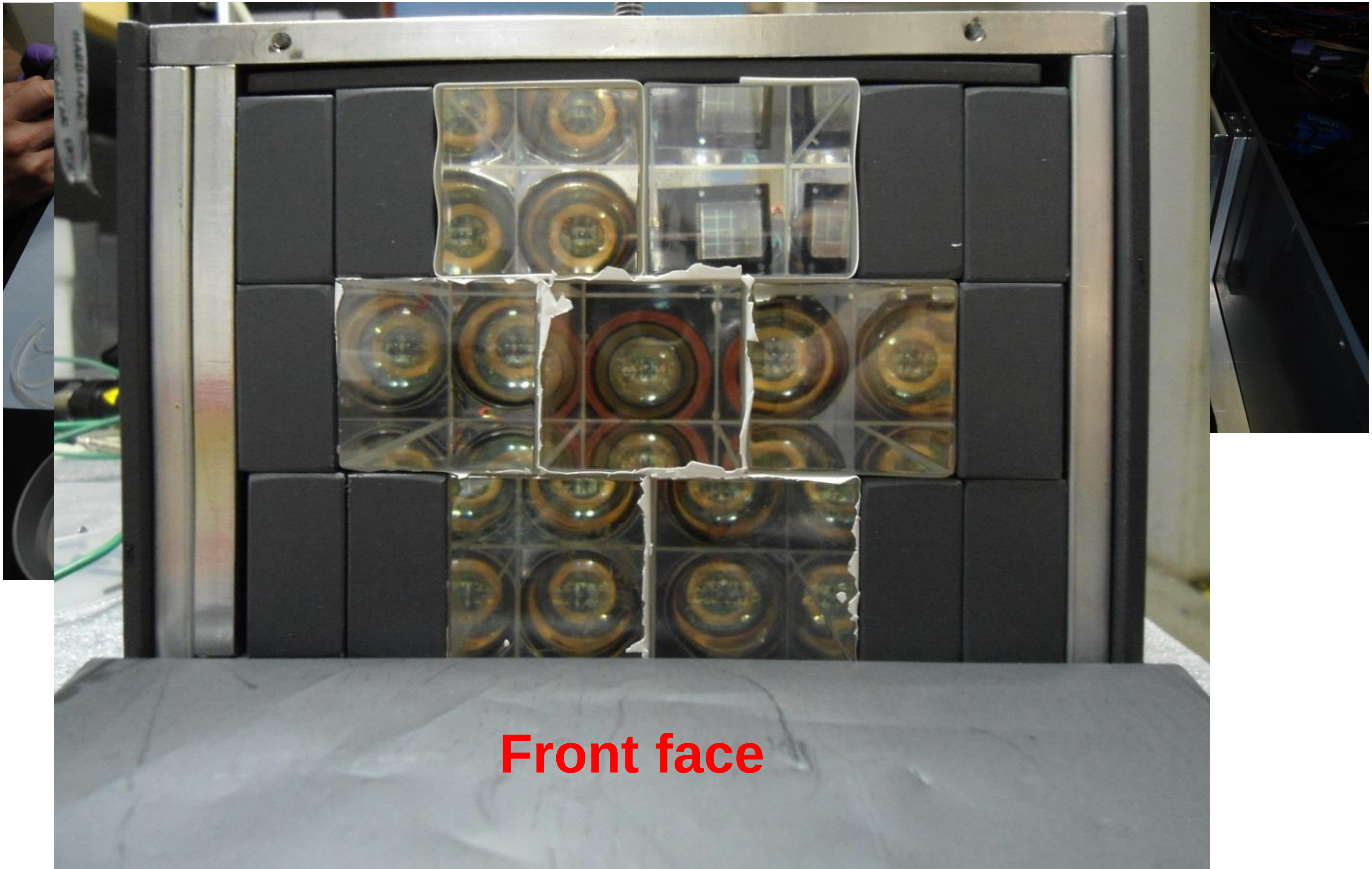
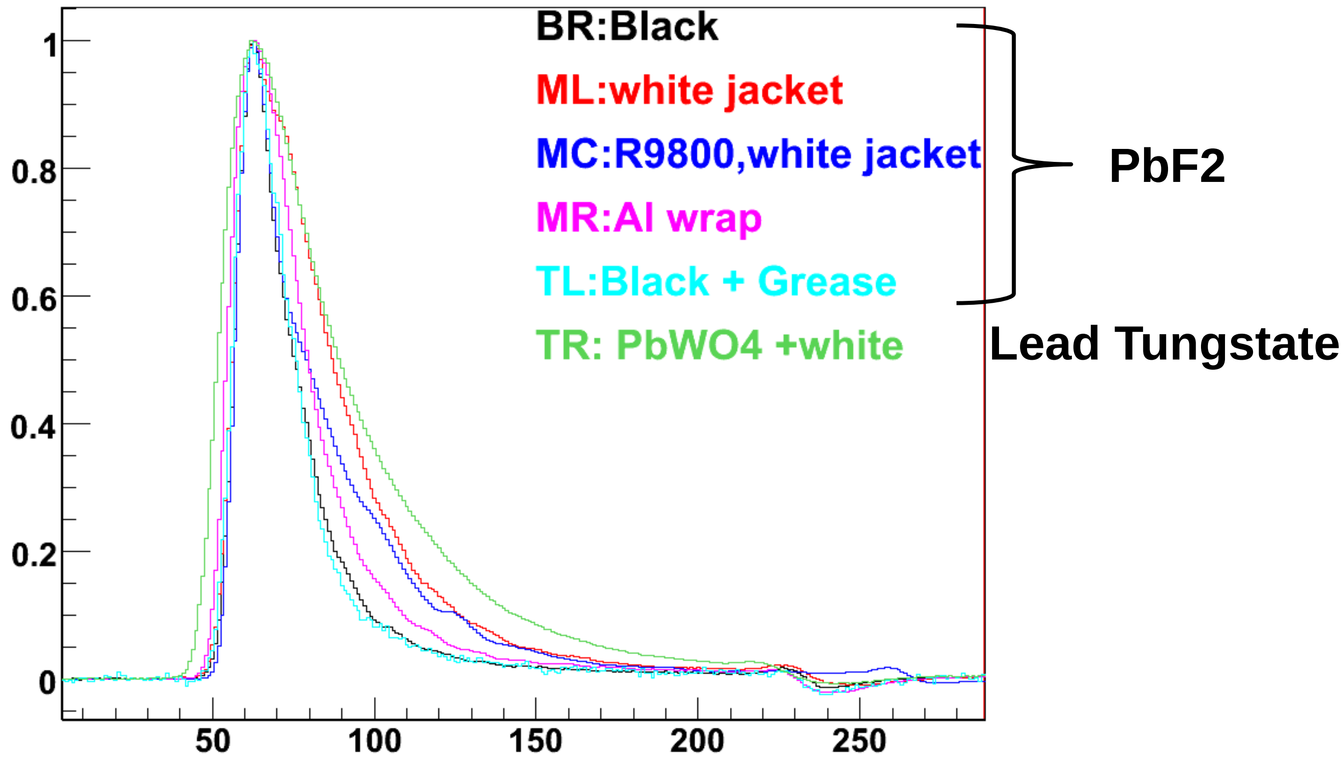
Our first PbF_2 prototype array was tested with various wrappings, couplings, and readout at FNAL



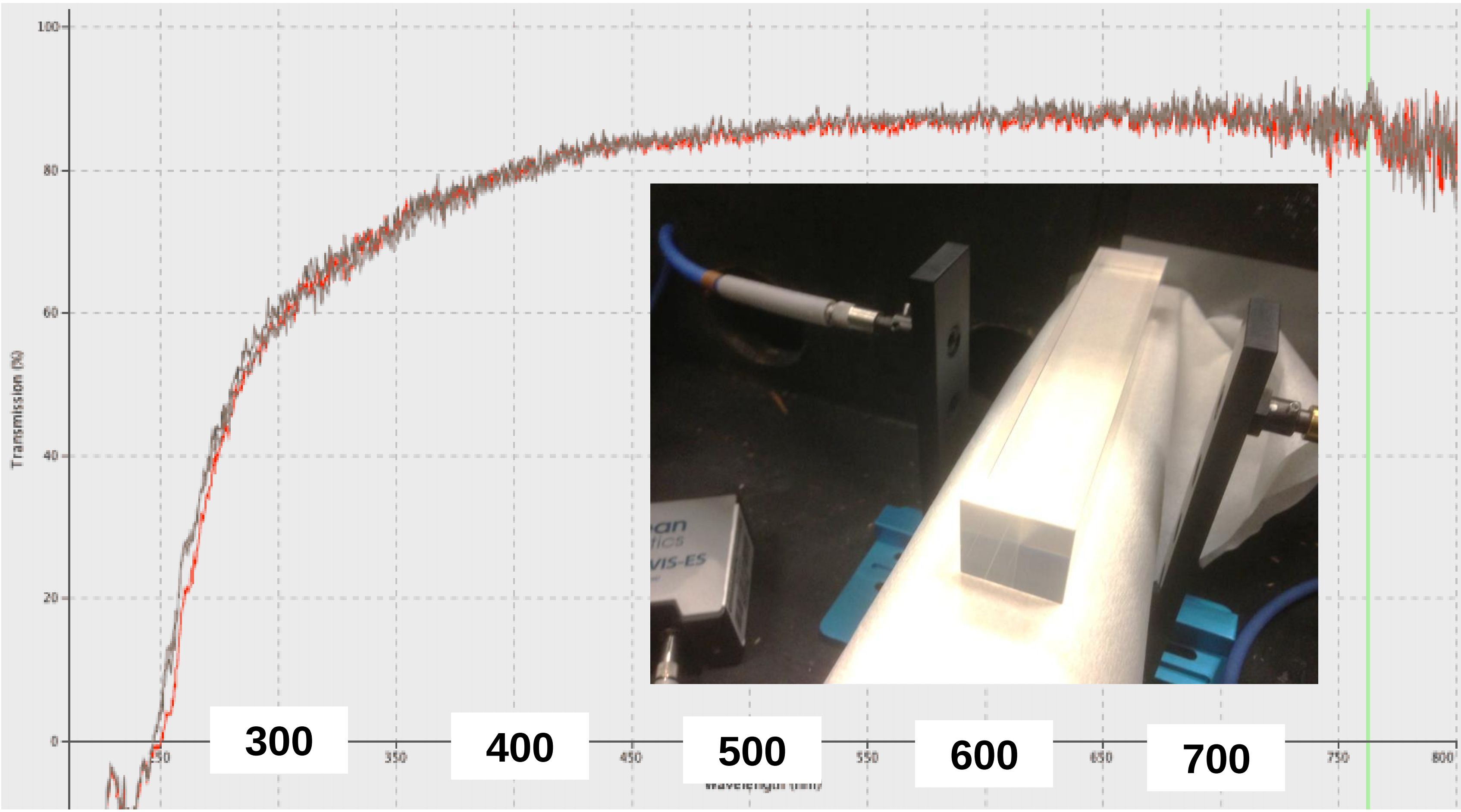
Pulse Shapes vs. Wrappings



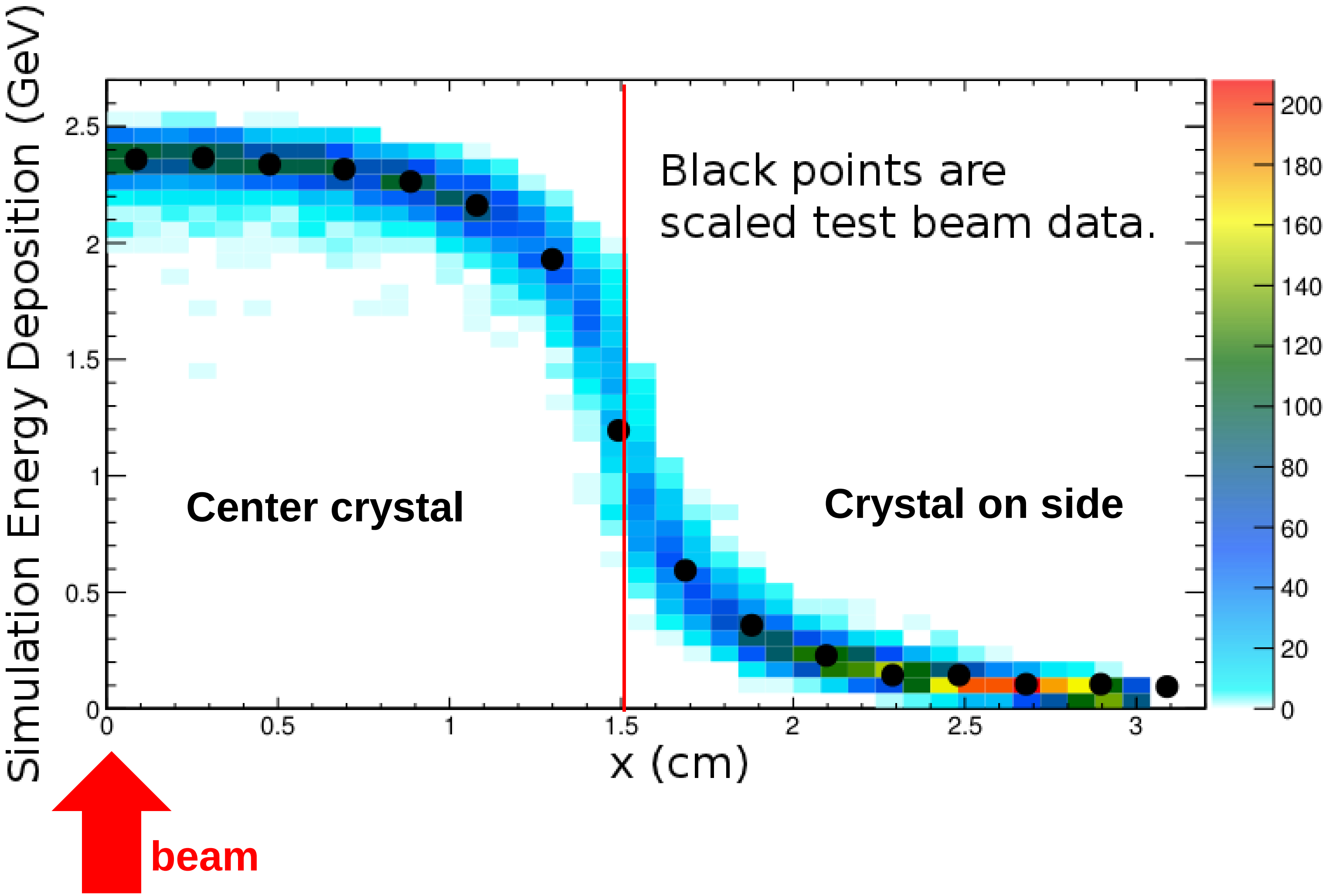
Element	Ends	Jacket	Crystal	FWHM (ns)	FW20%M (ns)
BR	Black	Black	PbF2	8.0	13.6
ML	Black	White	PbF2	12.4	22.4
MC	White	White	PbF2	8.8	20.4
MR	Al	Aluminum	PbF2	10.0	17.2
TR	White	White	PbWO4	15.2	29.2

Lead Tungstate

Ocean Optics spectrometer used to measure transmission vs. wavelength

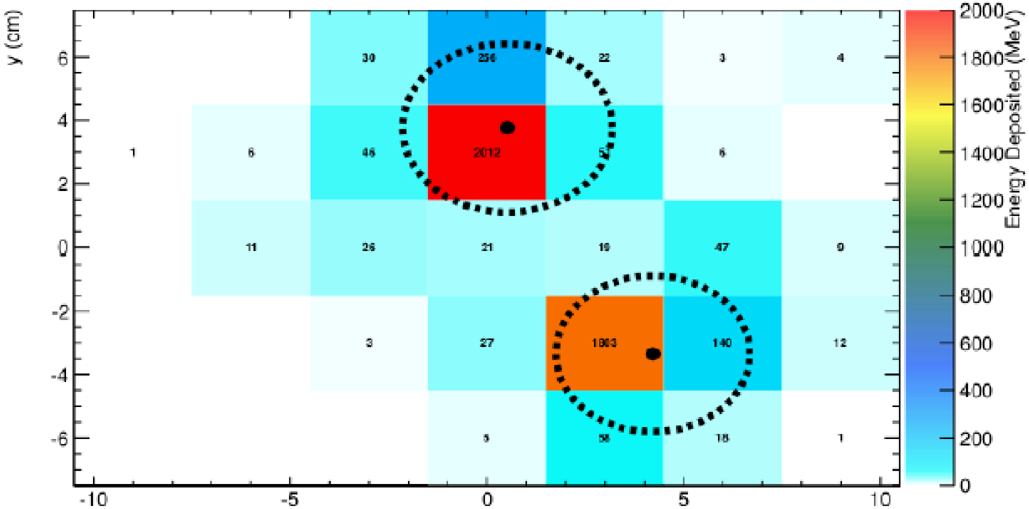


Moliere Radius / Energy Sharing
GEANT Simulation vs Measurement in Test Beam

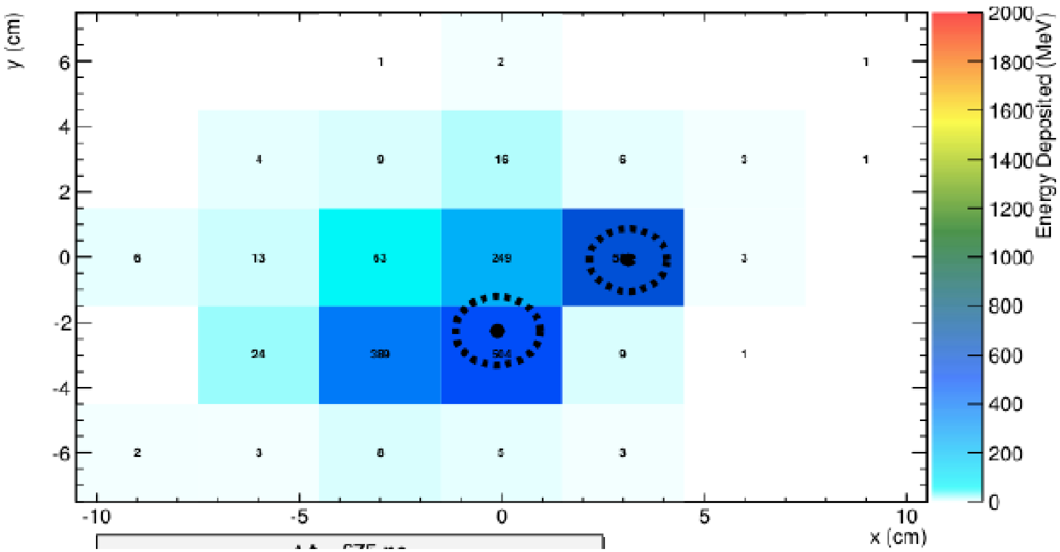


Binned beam impact points compared to continuous simulation

A 6 x 9 Array will be built for each of the 24 Calorimeter stations. Typical shower sizes and cluster separations, but TIMING (two-pulse resolution will be critical)



Relatively Easy with a good algorithm



Some pileup events will not resolve by space

Silicon Photo-Multipliers

MPPCs

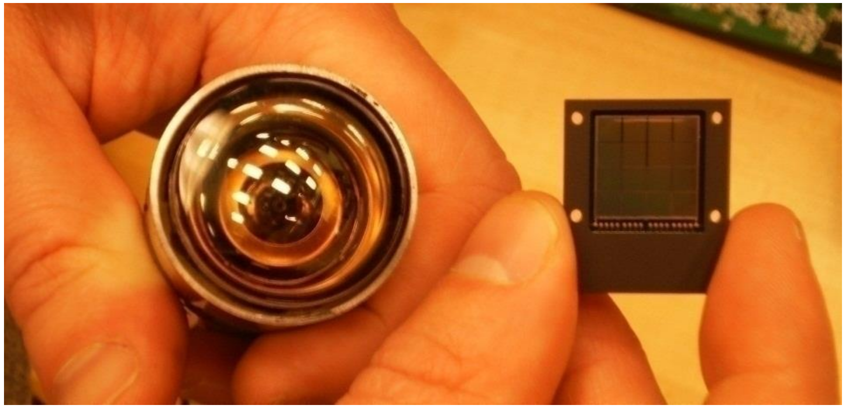
G-APDs

…

vs. PMTs

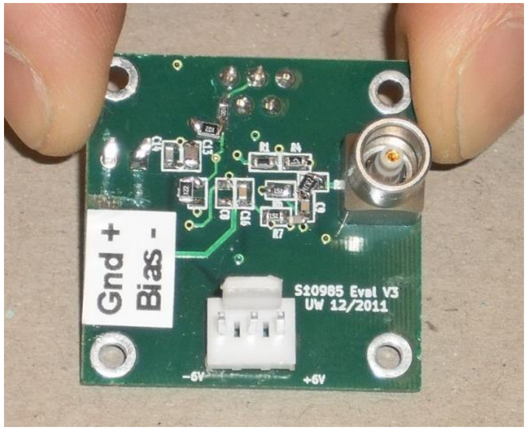
Comparing SiPMs to fast PMTs. Can the former replace the latter ?

Hamamatsu R9800 PMT



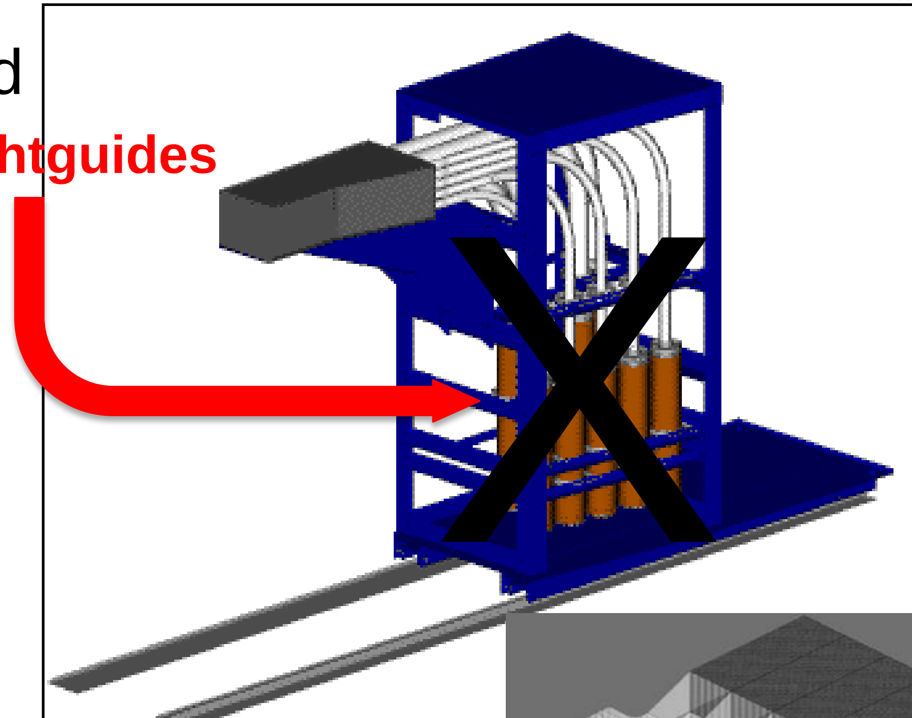
Hamamatsu 16 channel SiPM

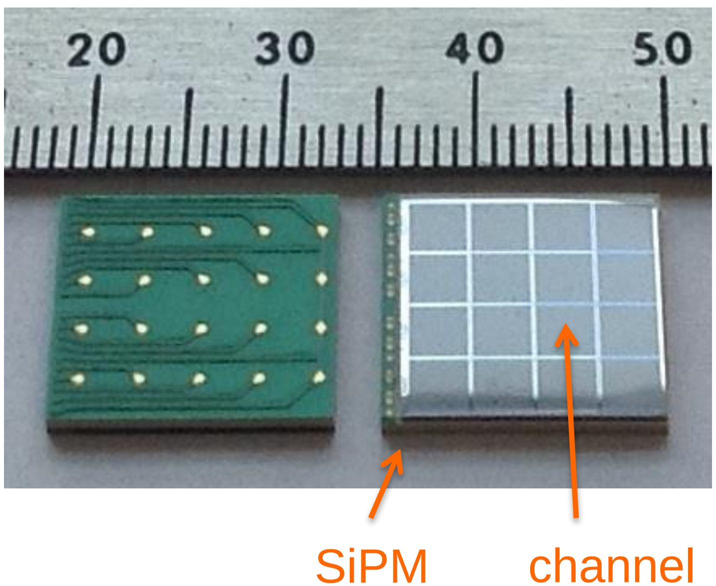
... and electronics for SiPM

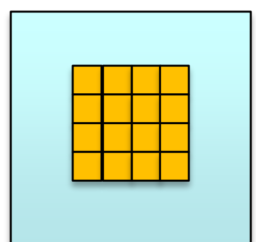


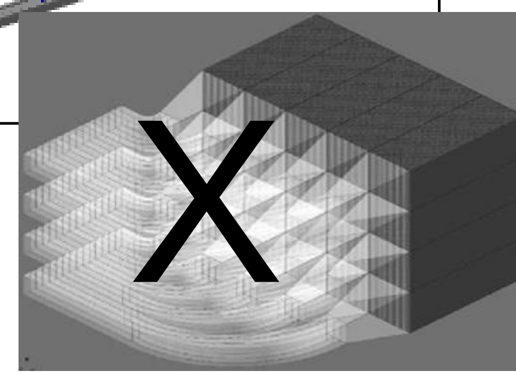
Why we'd like to use SiPMs if we can

- Can work in 1.45 T field
  - Mount on board; **NO lightguides**
- Non-magnetic
- Lower cost



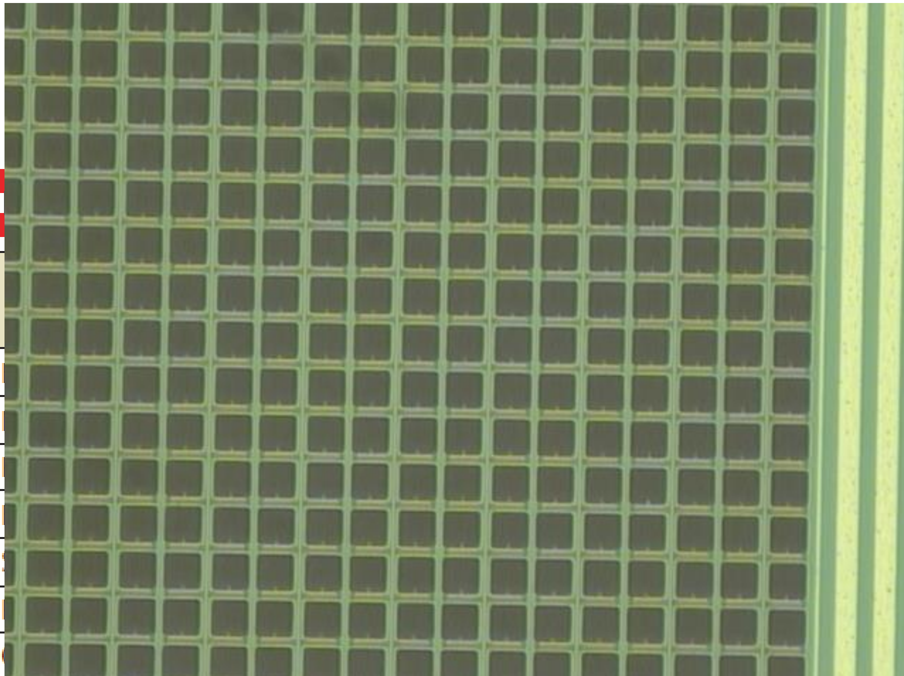






Crystal : SiPM size comparison. ~ 4:1 Is it enough ?

Our (working) Design Choice is this 12 x 12 mm2 16-channel SiPM from Hamamatsu

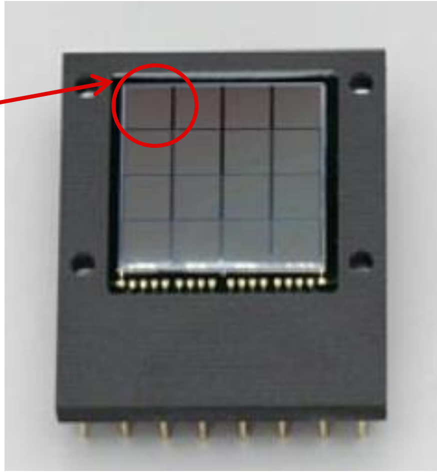


noted)

			S10362-33 series	
			-050C	-100C
			3 × 3	
			3600	900
			50 × 50	100 × 100
			61.5	78.5
			320 to 900	
			440	
			70 ± 10 *2	
Dark count *3	-	4	6	8
Dark count Max. *3	-	8	10	12
Terminal capacitance	Ct	320		
Time resolution (FWHM) *4	-	500 to 600		
Temperature coefficient of reverse voltage	-	56		
Gain	M	2.75×10^5	7.5×10^5	2.4×10^6

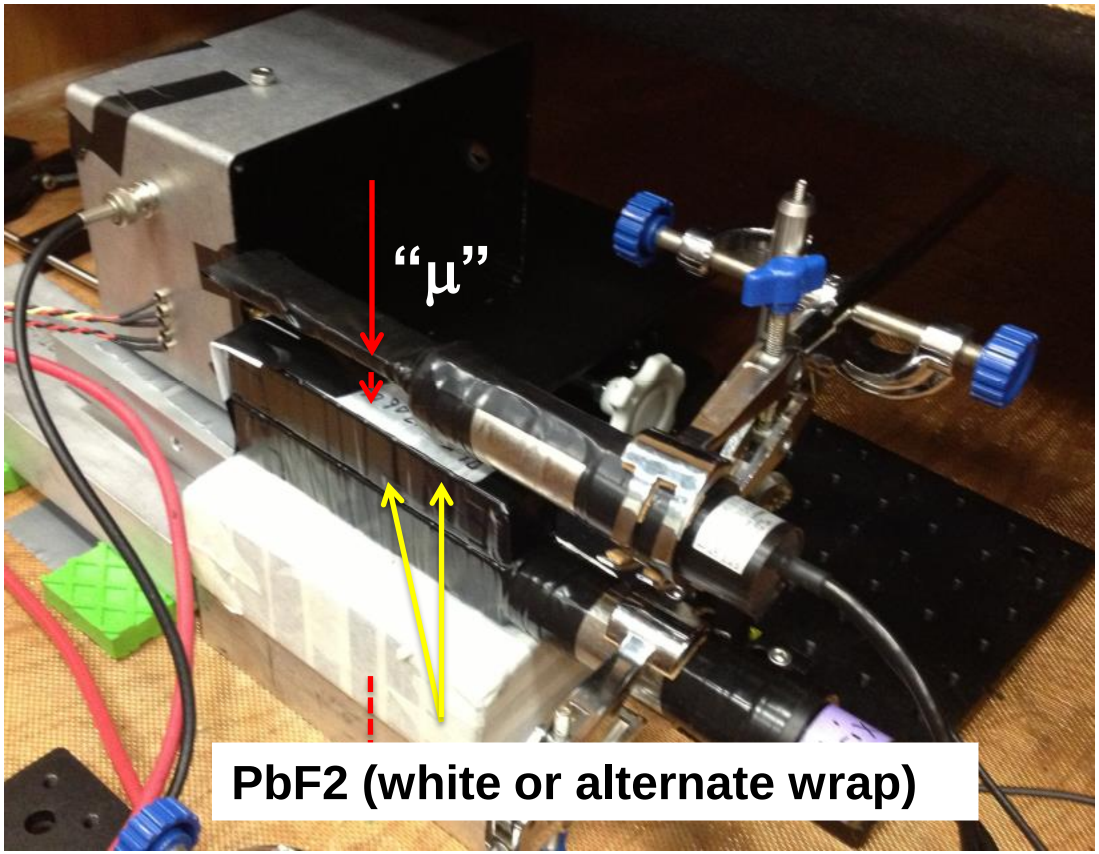
(Geiger mode avalanche photodiodes)

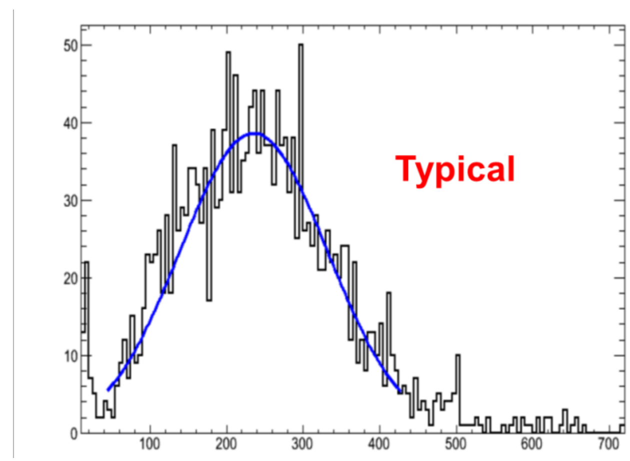
16 of these per unit



57600 individual photon detectors!

Because the larger SiPMs are still small compared to the crystal, light yield is a big issue

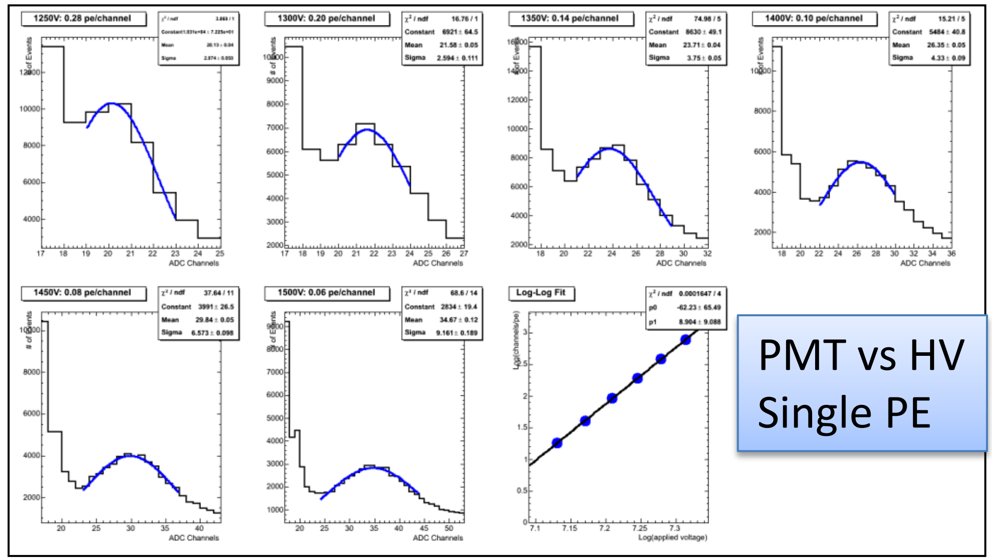




Bench Tests with Cosmic Rays and PMTs

Convert to photon yield and to SiPM expectation (will return to this again for SiPM)

- Low light level calibration with laser turned down



- Energy loss $\Delta E = 26.8 - 32.17[MeV]$
- Photons produced $\frac{d^2N}{dEdx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$ $N_{\gamma,tot} = 1030\text{-}1240.$

  - Black Wrapping: ~24 ± 4
  - White Wrapping: ~55 ± 6

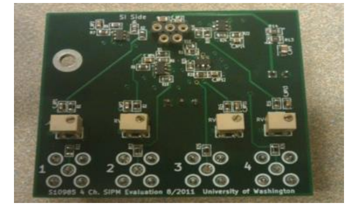
This will lead to an important test at SLAC

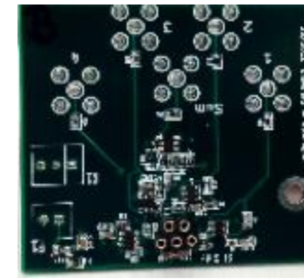
Many vendors …

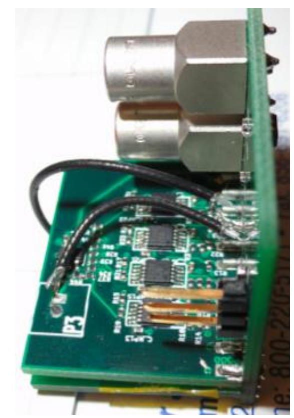
- We are also evaluating SiPMs from all major vendors

SiPMs Require Custom Summing Board that affect the pulse shape

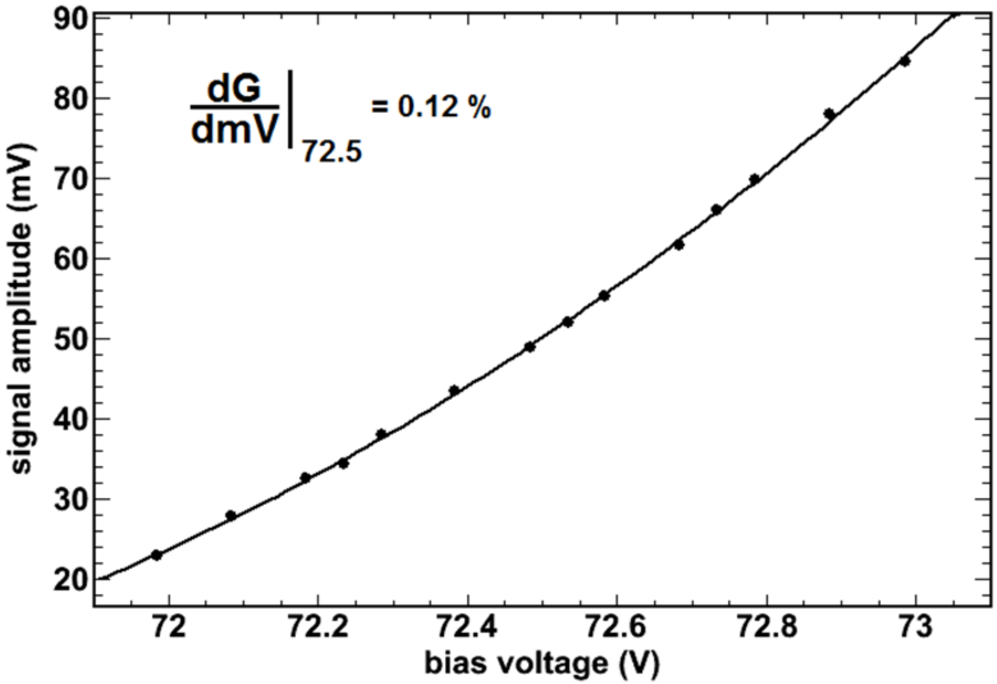
board	chann	
A	2x2	4 individually readout voltage amplifiers with trim pots for individual bias voltage change
B	2x2	no trim pots, voltage op amp with small load resistor.
C	2x2	all channels are summed first via a 2.5 Ohm load resistor and then amplified in two stages
D	4x4	First 16 ch board. 1 amp per 2 channels
E	4x4	Amp for each channel
F	4x4	Transimpedance amp (was ringing)
G	4x4	Individual shunt resistors and passive adding network with 2 gain stages; voltage amplifiter
F	4x4	G board modified for current amplifier; This board has passed many requirements tests

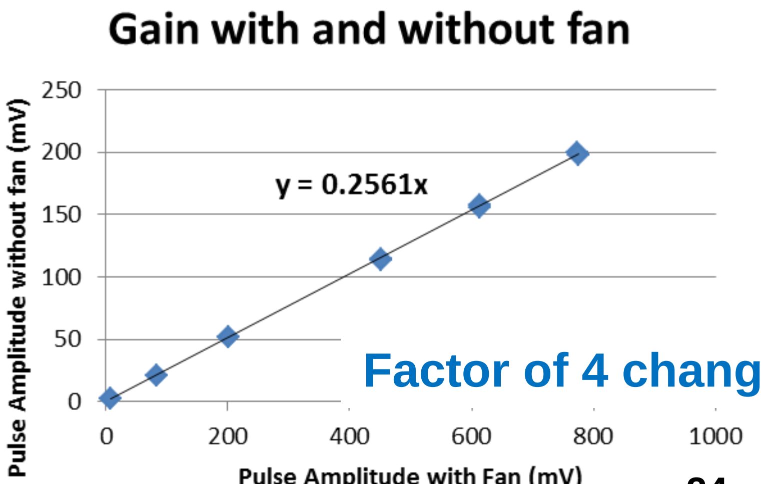






Gain is highly sensitive to Over-voltage Bias or Temperature





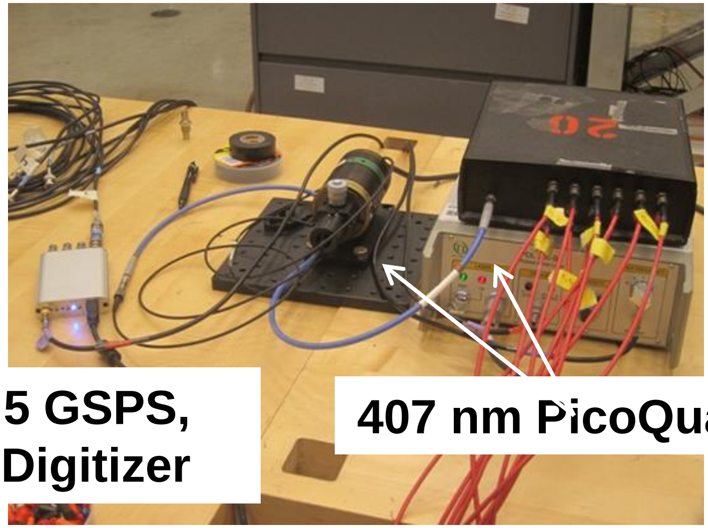
Factor of 4 change !

Essentially the same effect.

The breakdown voltage of the diode is temperature dependent

Evaluation tools: Test Setup at UW

Muon g-2



DRS 5 GSPS,
4-ch Digitizer

407 nm PicoQuant Laser

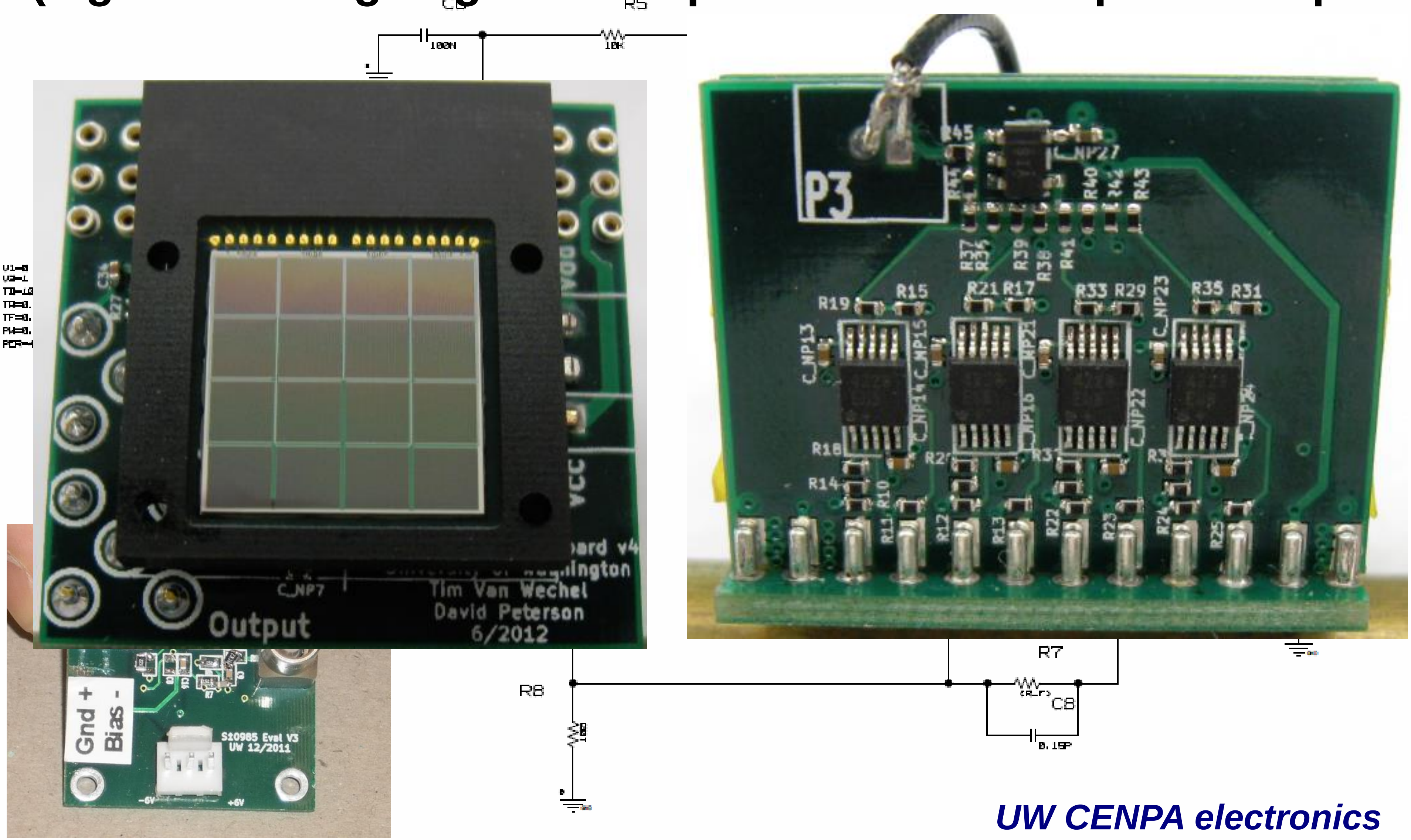
→ **1:12 E821 Optical Splitter**

USB-driven Neutral Density Filter wheel for remote intensity variation

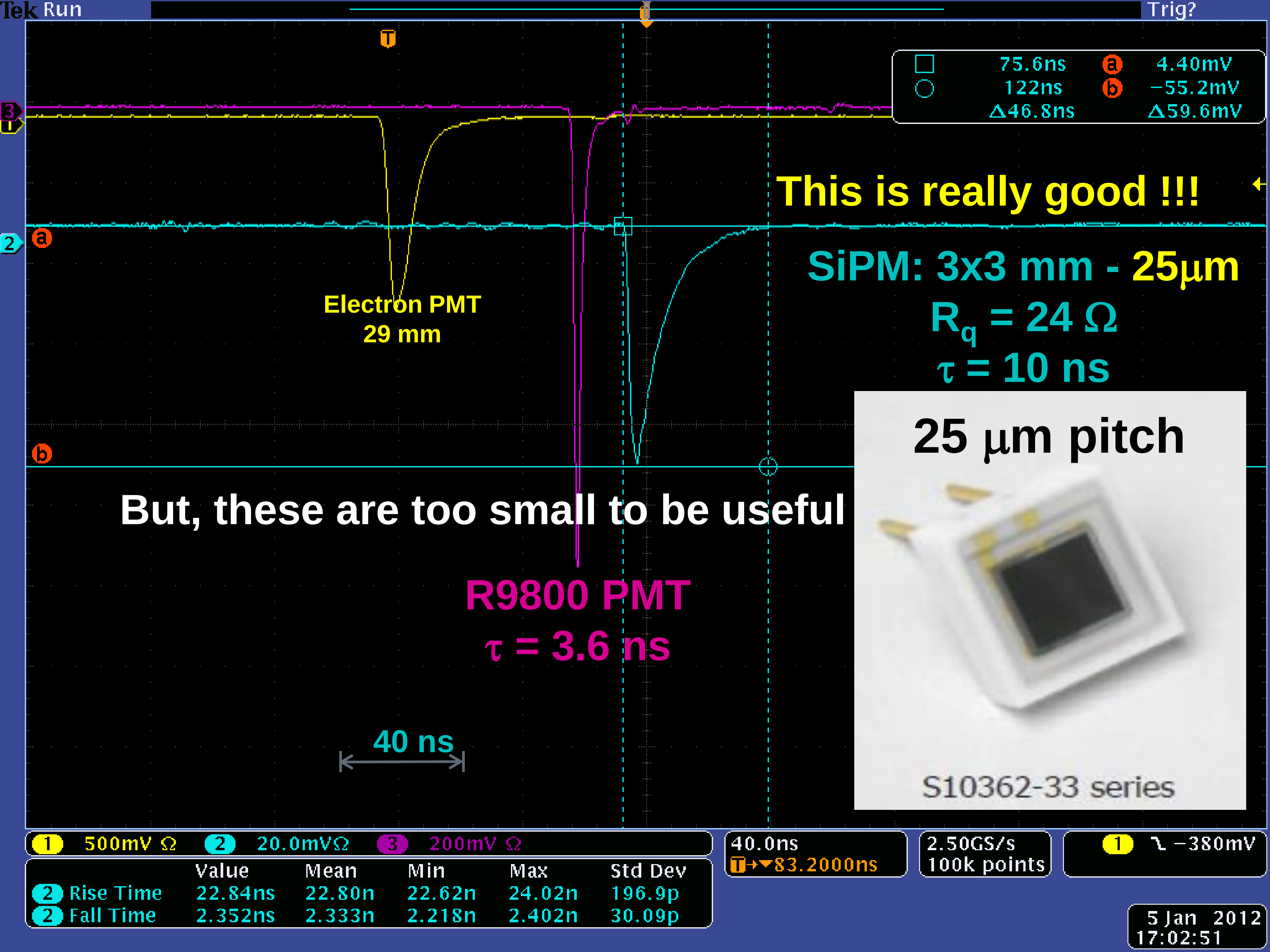
DRS4, PSI
bandwidth of 950 MHz
sampling frequency from 0.7 to 5 GSPS

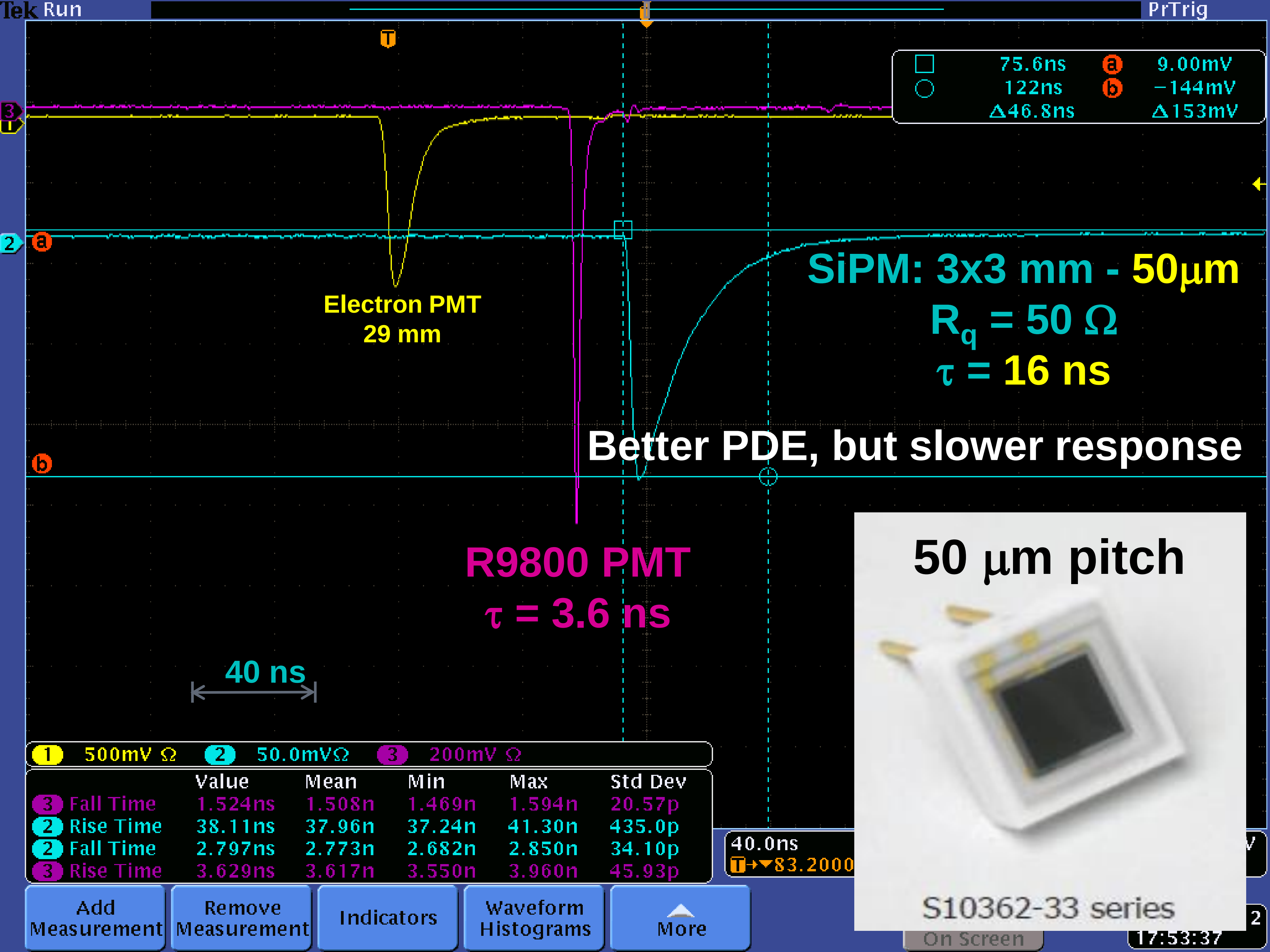
SiPMs require custom-made amplifiers and summing circuits. Pulse shapes affected

(significant ongoing effort to preserve intrinsic pulse shape



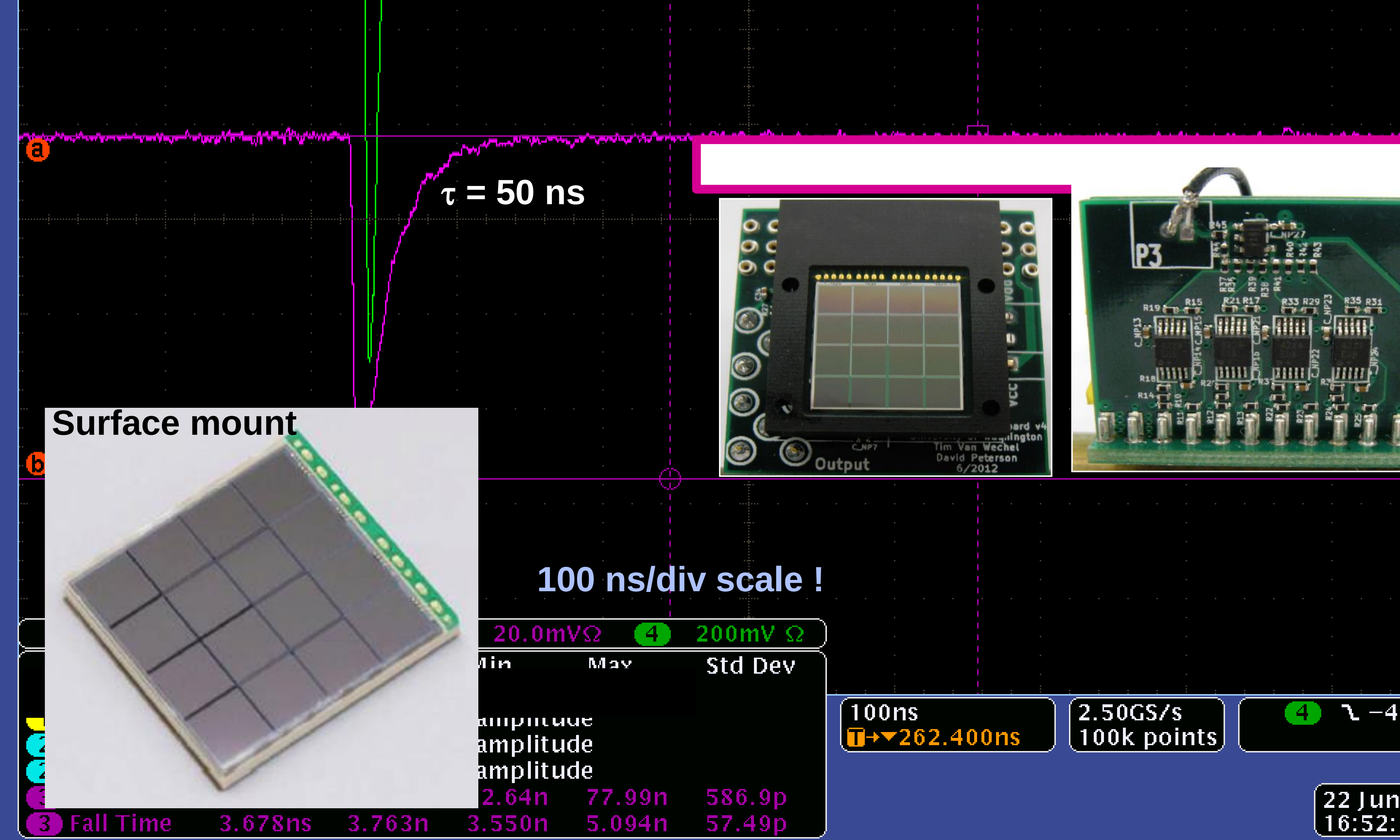
UW CENPA electronics


Tek Run
Trig?
75.6ns
122ns
Δ46.8ns
4.40mV
−55.2mV
Δ59.6mV
This is really good !!!
SiPM: 3x3 mm - 25µm
R$_q$ = 24 Ω
τ = 10 ns
Electron PMT
29 mm
25 µm pitch
But, these are too small to be useful
R9800 PMT
τ = 3.6 ns
40 ns
S10362-33 series
1 500mV Ω
2 20.0mVΩ
3 200mV Ω
40.0ns
T→▾83.2000ns
2.50GS/s
100k points
1 ⌐ −380mV
Value Mean Min Max Std Dev
2 Rise Time 22.84ns 22.80n 22.62n 24.02n 196.9p
2 Fall Time 2.352ns 2.333n 2.218n 2.402n 30.09p
5 Jan 2012
17:02:51



Tek Run
PrTrig
75.6ns
122ns
Δ46.8ns
9.00mV
−144mV
Δ153mV
Electron PMT
29 mm
SiPM: 3x3 mm - 50µm
Rq = 50 Ω
τ = 16 ns
Better PDE, but slower response
R9800 PMT
τ = 3.6 ns
40 ns
50 µm pitch
S10362-33 series
1 500mV Ω
2 50.0mVΩ
3 200mV Ω
Value Mean Min Max Std Dev
3 Fall Time 1.524ns 1.508n 1.469n 1.594n 20.57p
2 Rise Time 38.11ns 37.96n 37.24n 41.30n 435.0p
2 Fall Time 2.797ns 2.773n 2.682n 2.850n 34.10p
3 Rise Time 3.629ns 3.617n 3.550n 3.960n 45.93p
40.0ns
83.2000
Add Measurement
Remove Measurement
Indicators
Waveform Histograms
More
On Screen
17:53:37

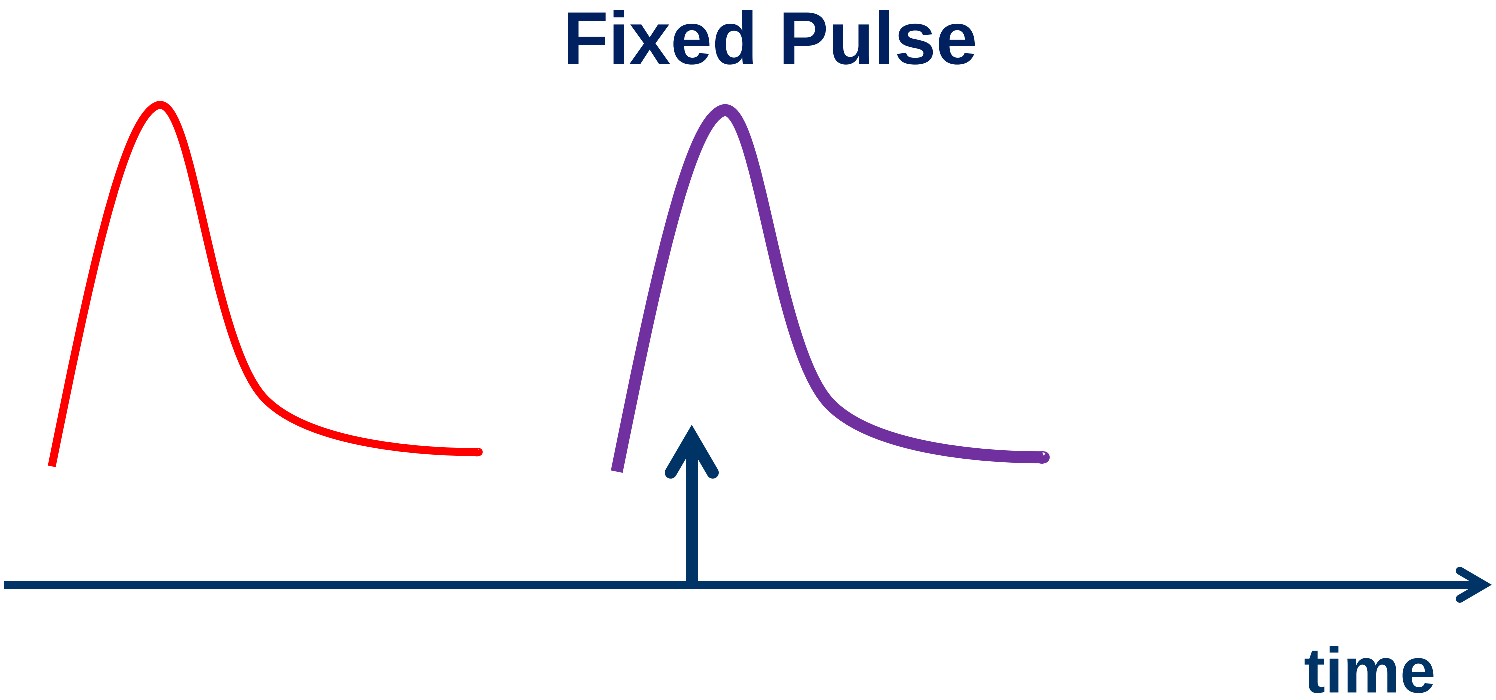
- Worse with 16 channels summed.
- Must minimize inductances and capacitances
- Must get lower average Quench Resistors on arrays



2-pulse resolution

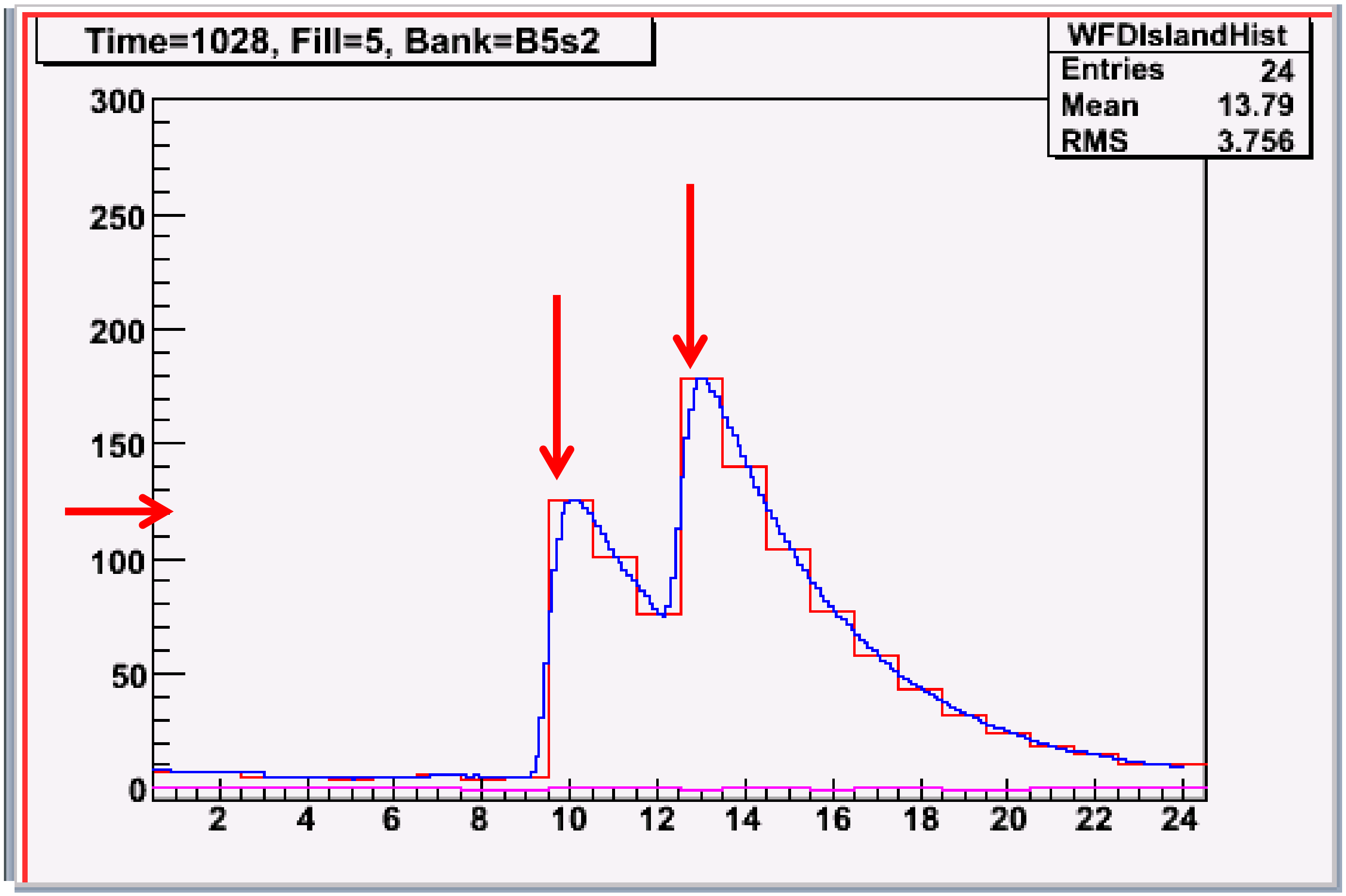
An example lab / simulation study

Two – pulse separation studies using real pulse shape templates and Monte Carlo

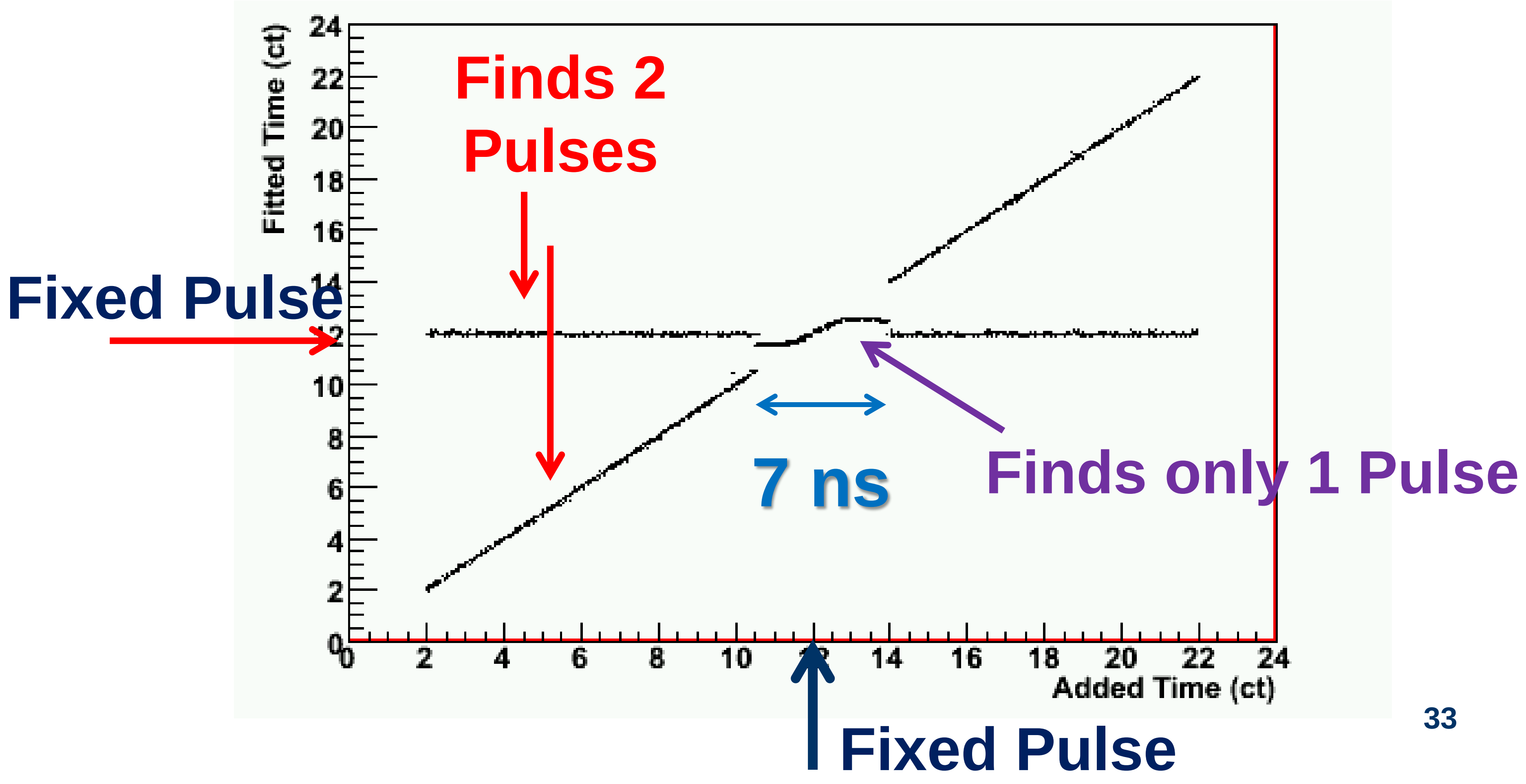


A realistic example with Δt = 6 ns

Actual SiPM waveforms at 500 MHz sampling

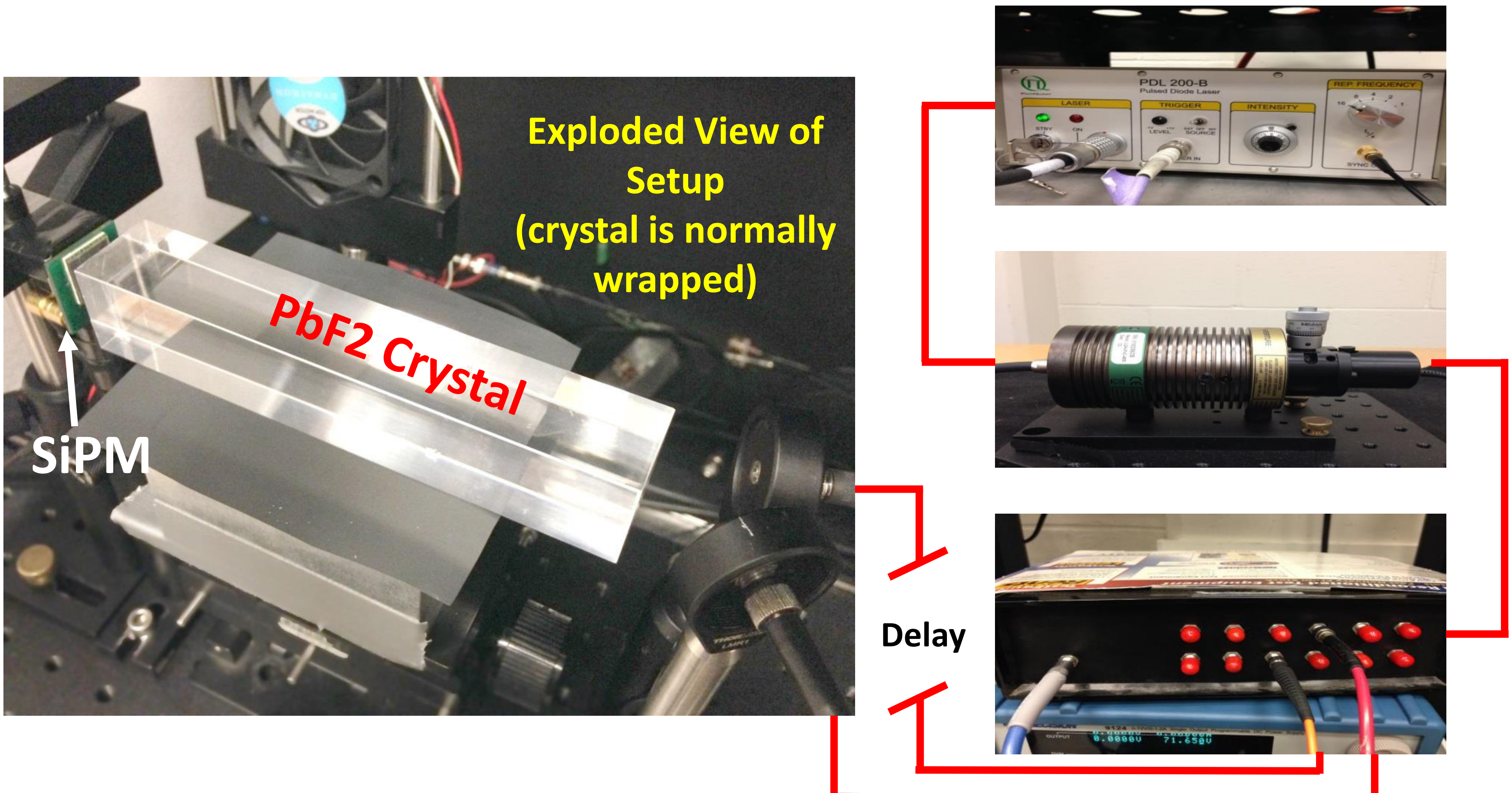


SiPM pulses are resolved for $\Delta t \sim 3.5$ ns

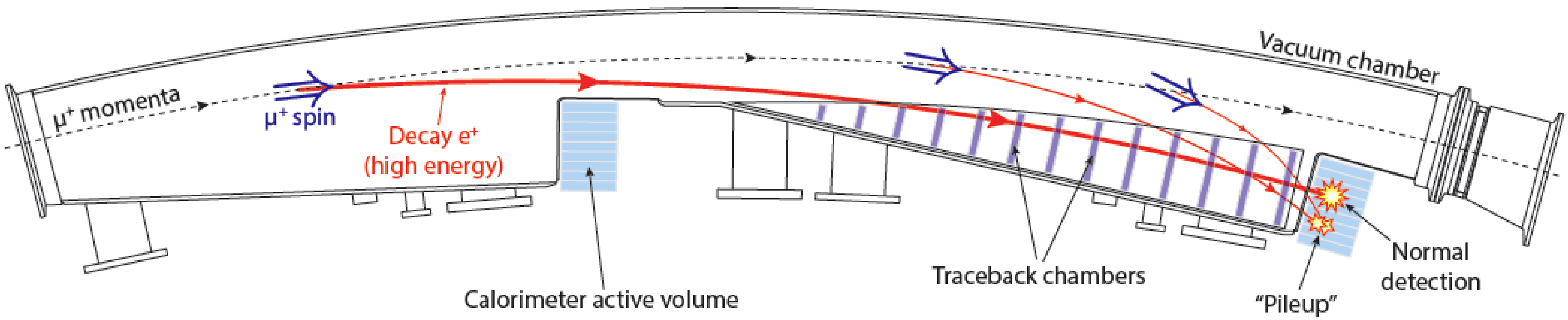


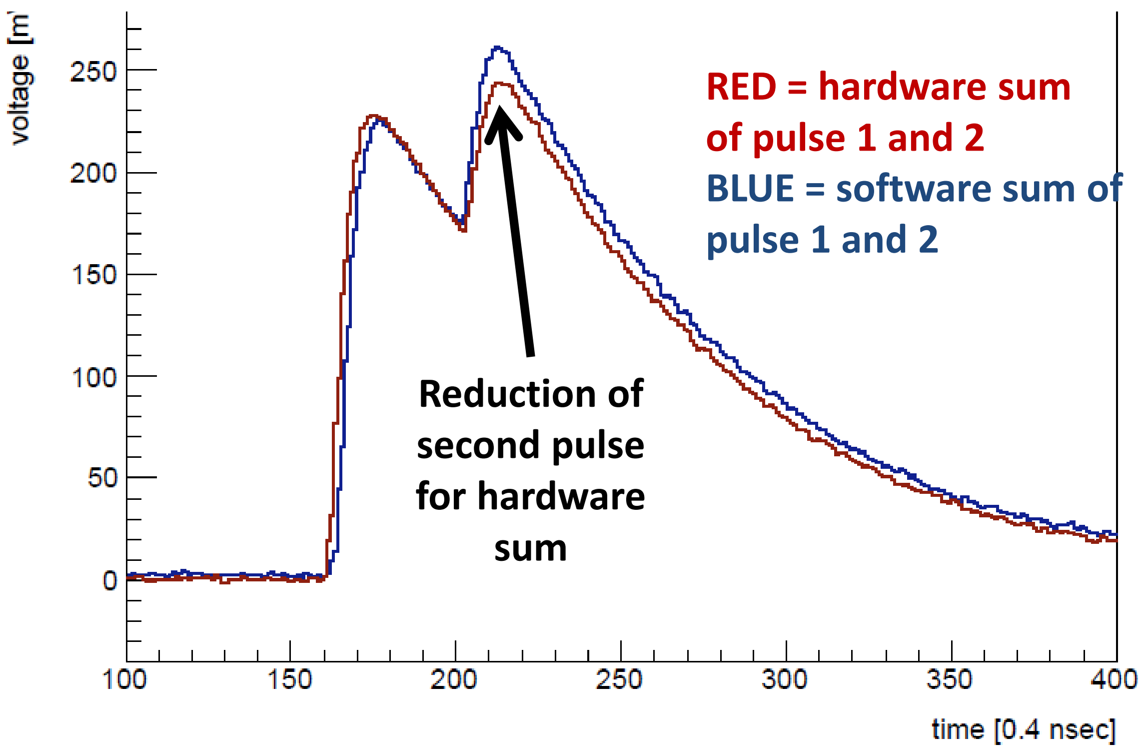
In the lab

- 407nm , ~100 ps long laser pulse split into two channels: E1 & E2
- E2 delayed by **optical fibers** [0 – 60 ns]
- Each pulse digitized at 2.7 GS/s, independently and together
- SiPM coupled to PbF2 crystal to ensure uniform illumination



For two events close in time in the same SiPM, how is the gain of the second pulse affected?





Map the response of the second pulse so it can be corrected if needed.

Function: : $G2(E_1, E_2, \Delta t)$

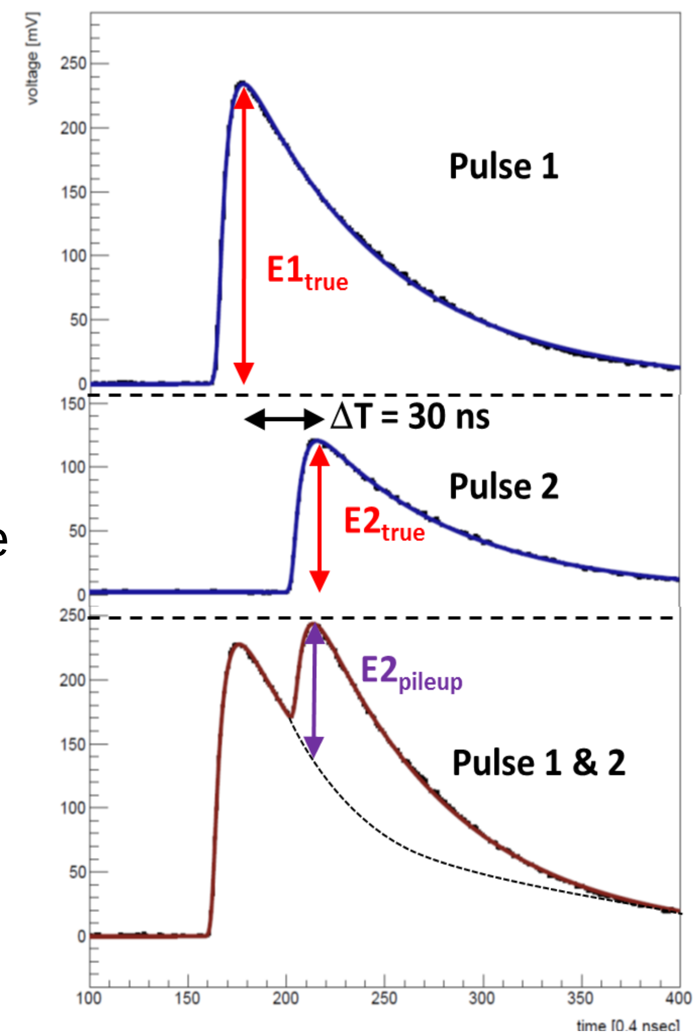
- *G2* is the gain and time of the second pulse
- E_i is the energy of the *ith* pulse
- $\boldsymbol{\Delta t}$ is the time separation

Pulse fitter model: single pulse

•Gaussian for laser pulse
•Exponential rise time for avalanche discharge
•Exponential decay time for SiPM recovery

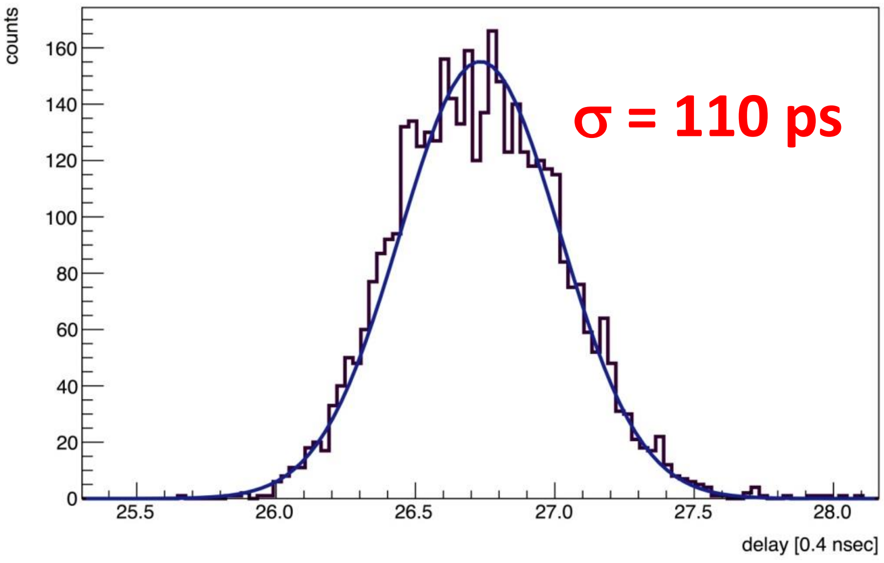
Pulse fitter model: pileup

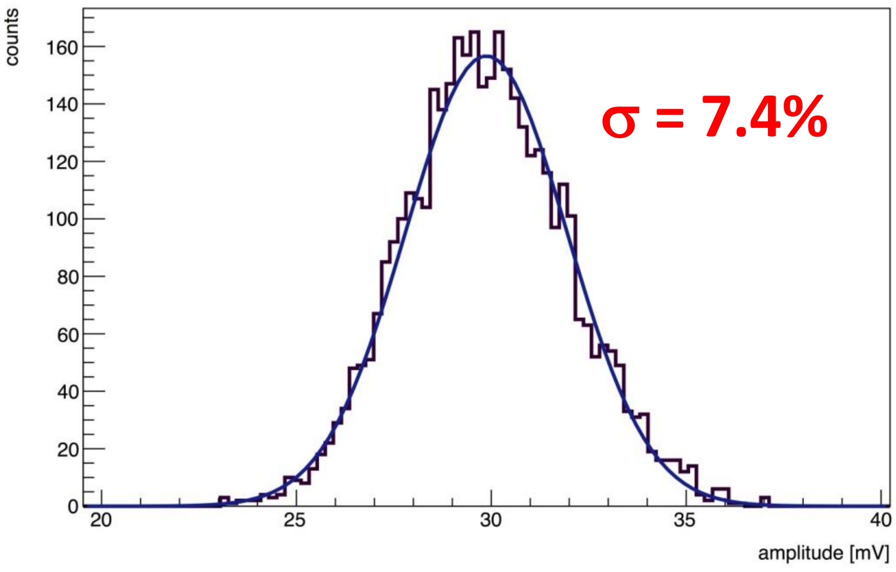
•Same laser pulse parameters
•Same rise and decay times
•Time delay



Energy and Time Resolution of Pulses

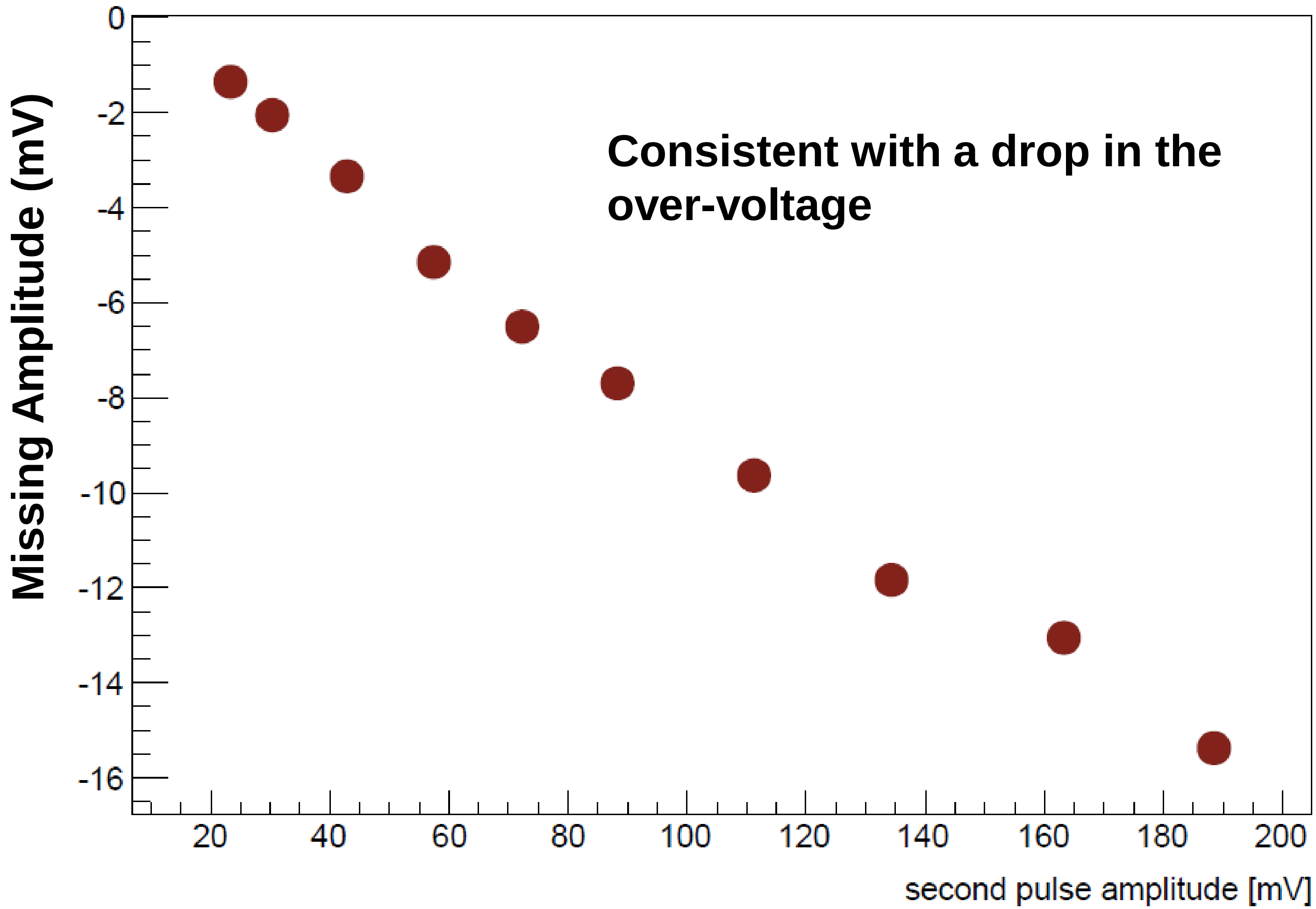
- Typical data set: 4000 fit results for energy and time of second pulse
- Time and energy resolution are very good even for low gain



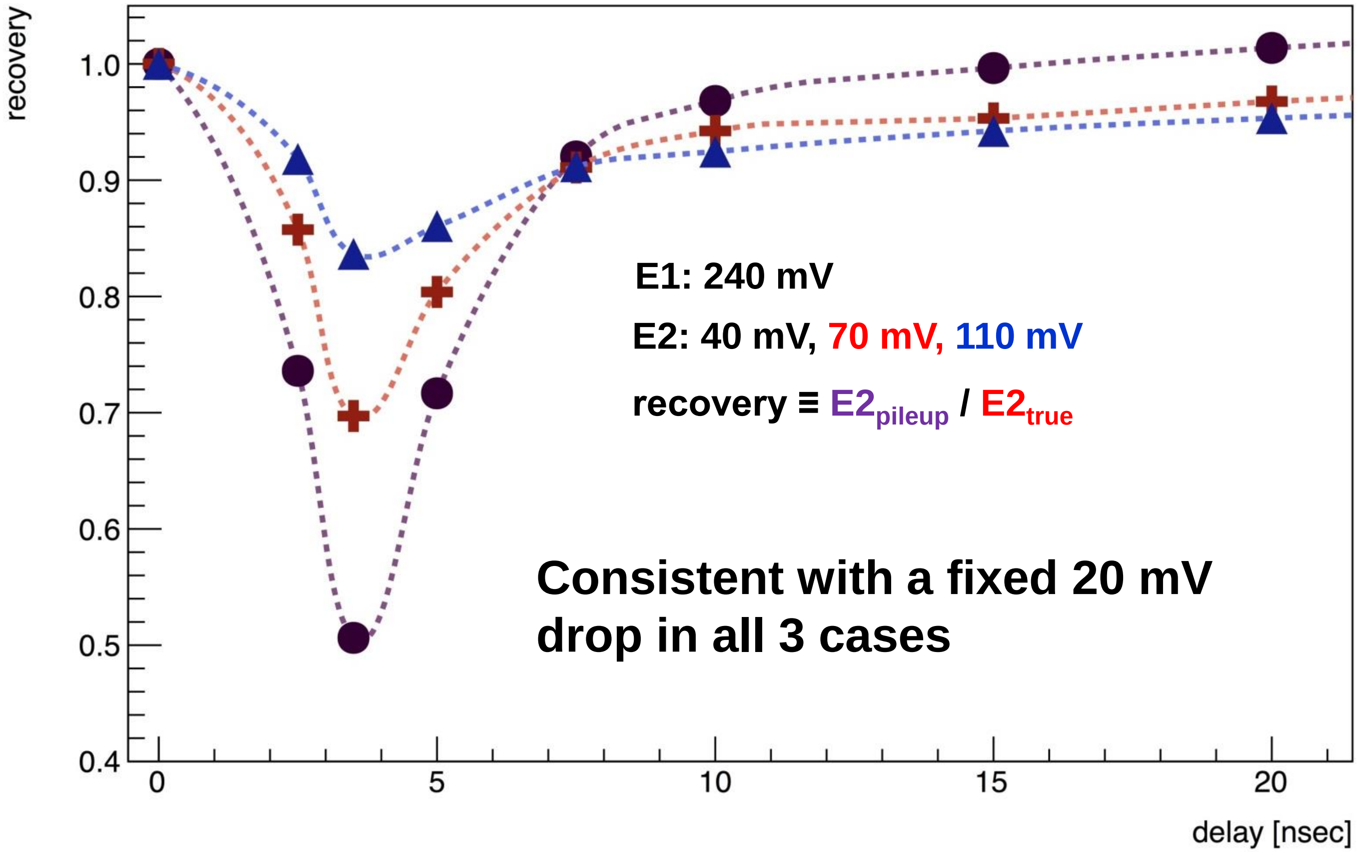


Pulse recovery depends on pulse size:

(missing amplitude is proportional to the amplitude)



Drop in 2nd pulse vs. time for 3 different 2nd pulse energies vs time Δt



These studies are continuing

Preliminary Results from SLAC test beam

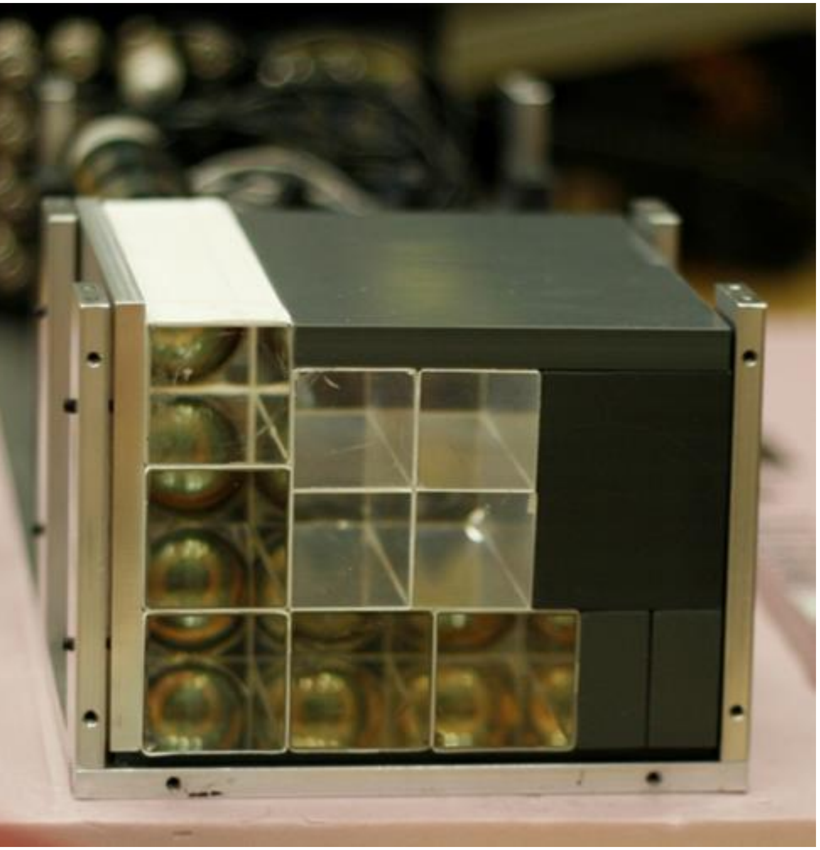
5 Hz, pure e^- in range 2.5 – 4 GeV (for us)

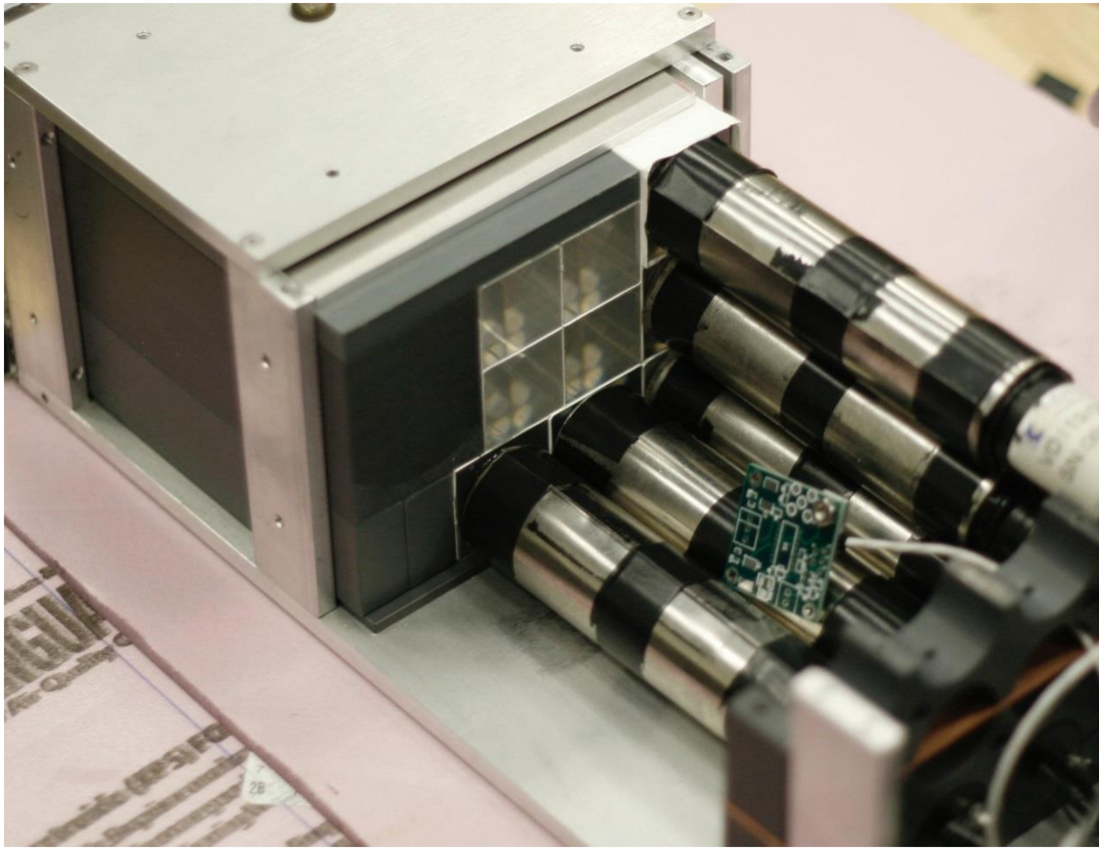
Prepared by Jarek Kaspar

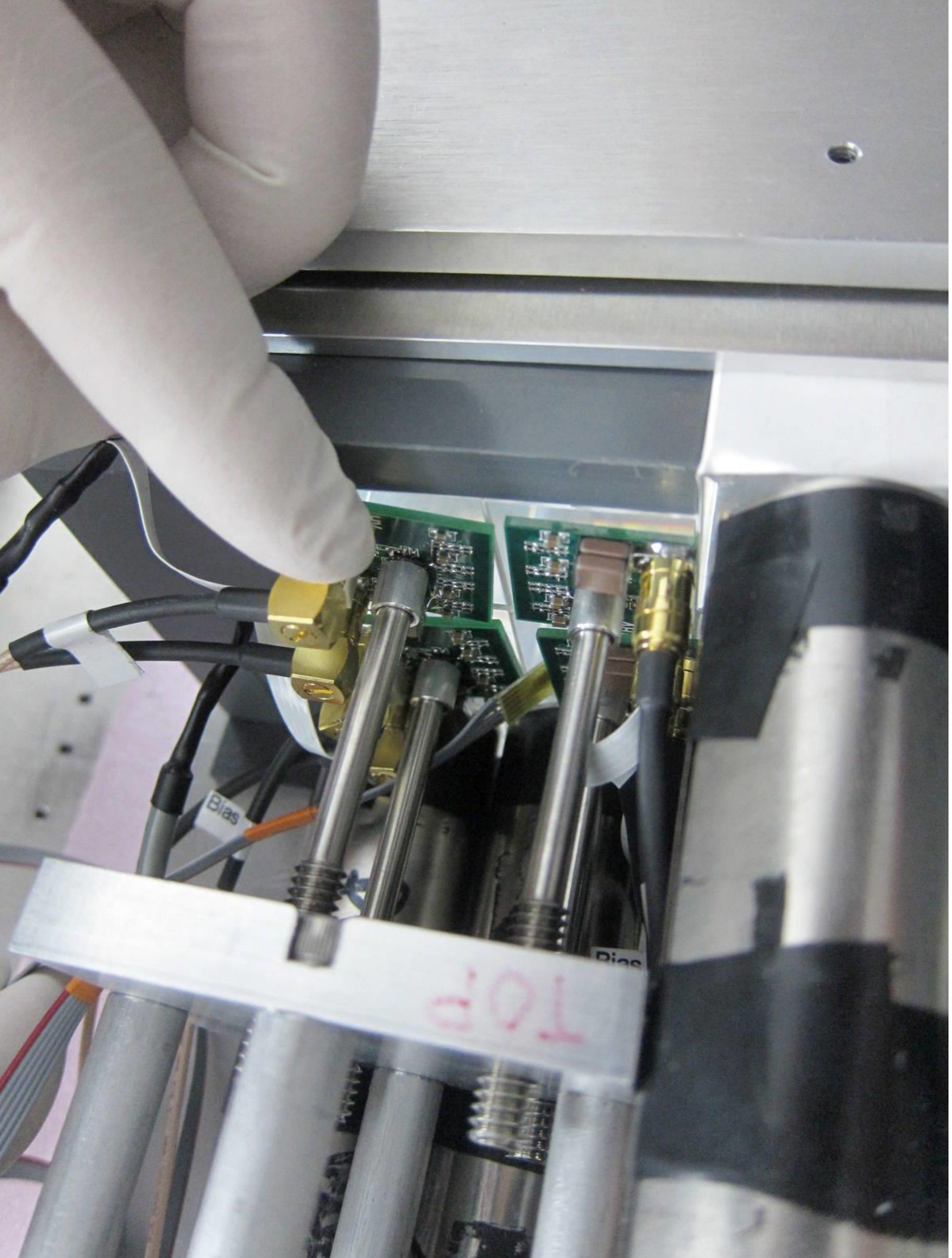
An array of 9 crystals

5 older 3x3 cm^2 and 4 newer 2.5x2.5 cm^2

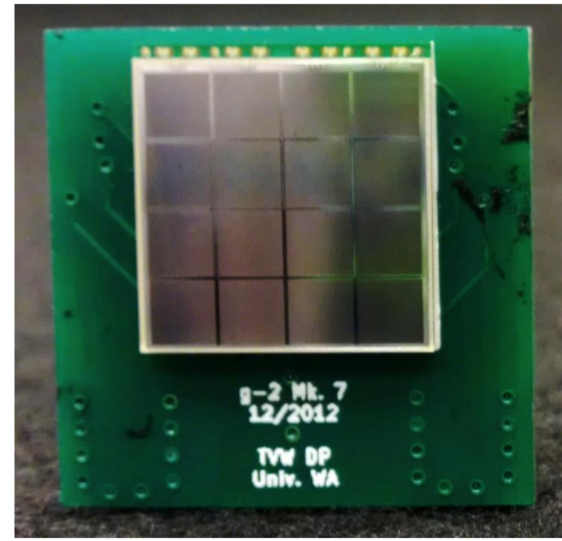
5 PMTs and 4 SiPMs

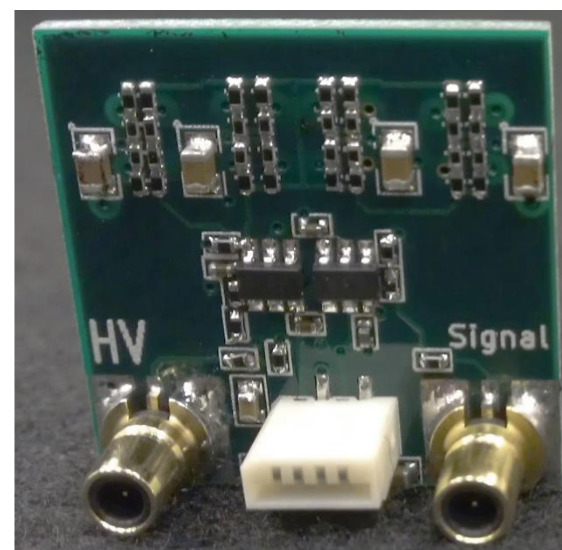


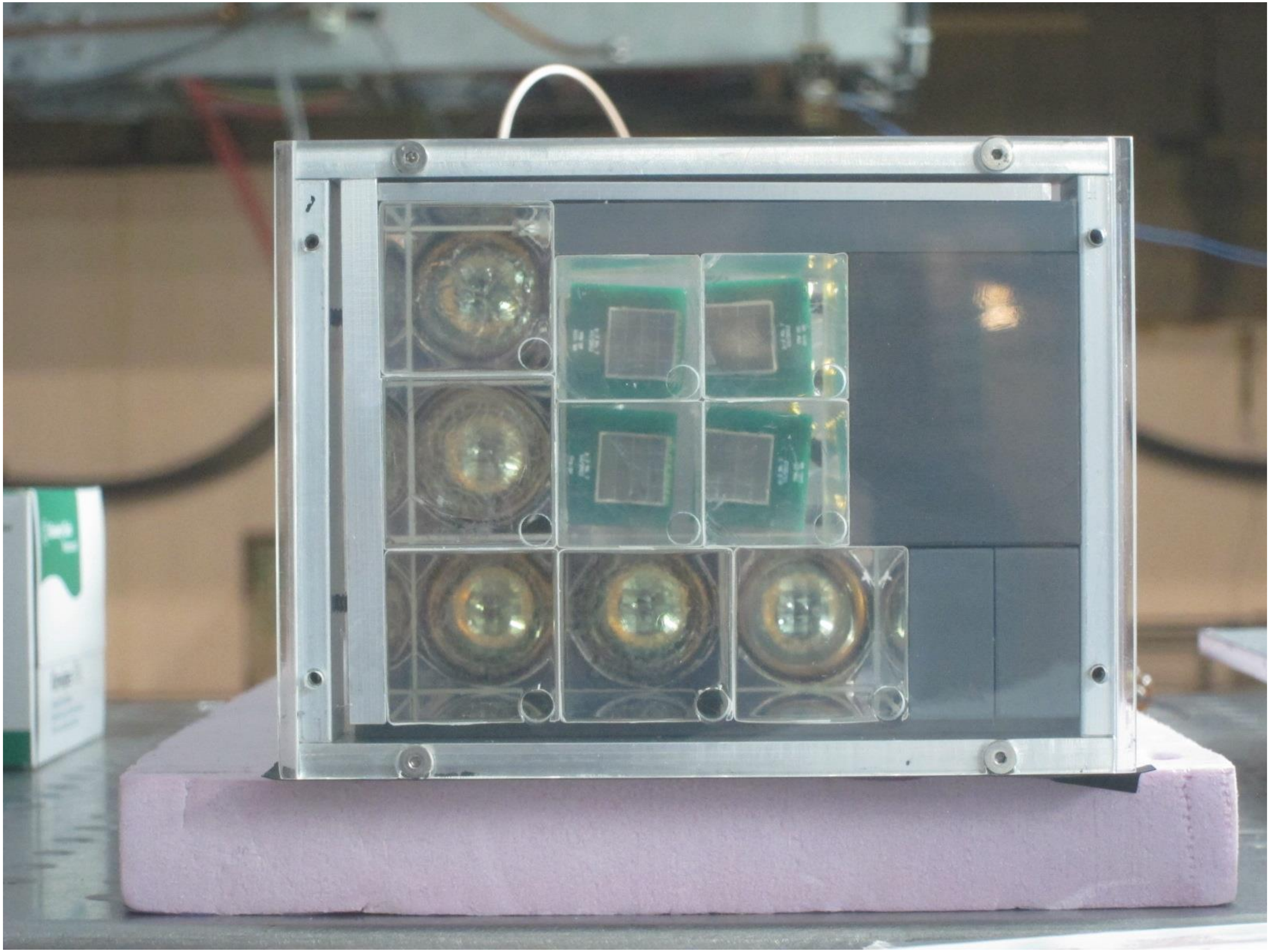




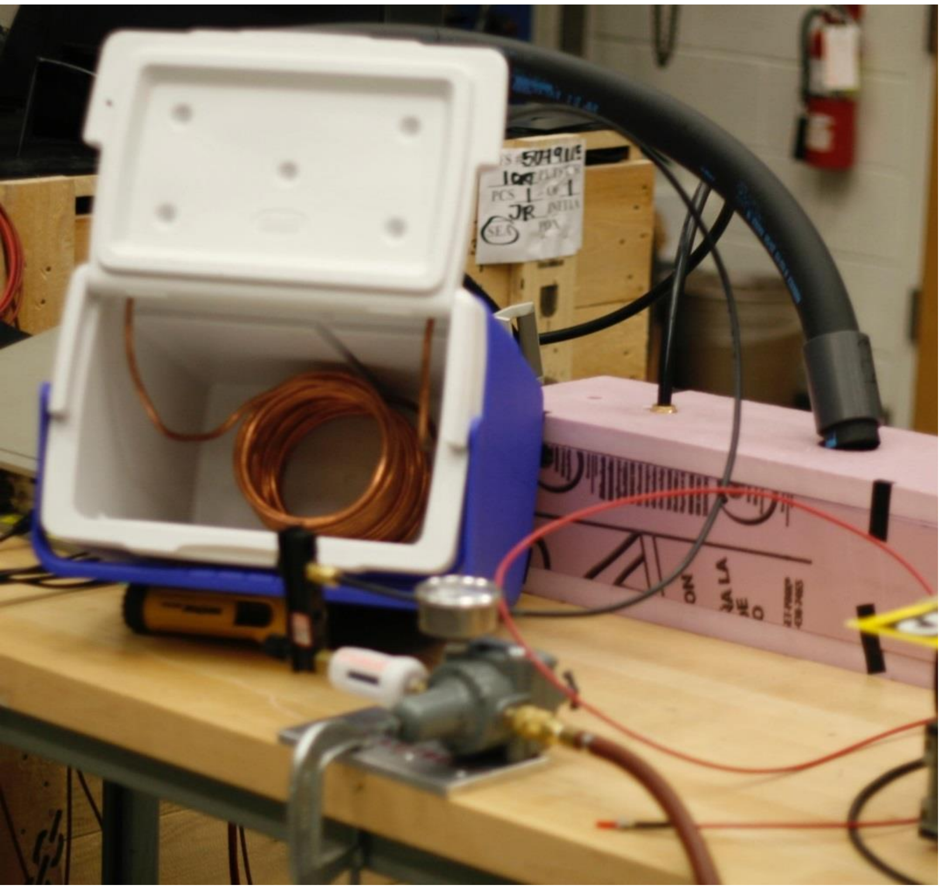
Add SiPMs



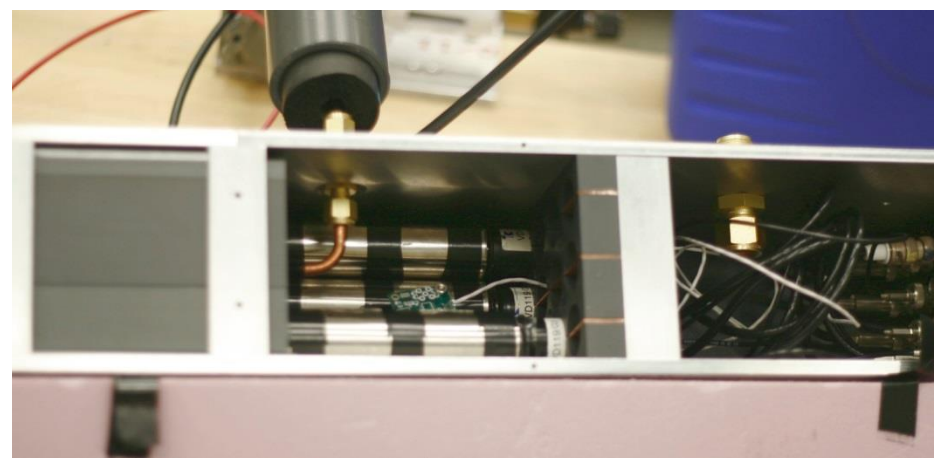




Stabilized temperature

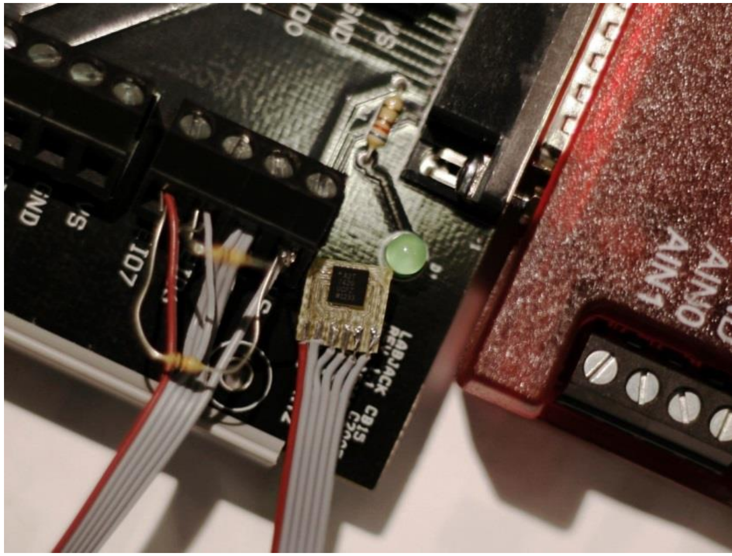


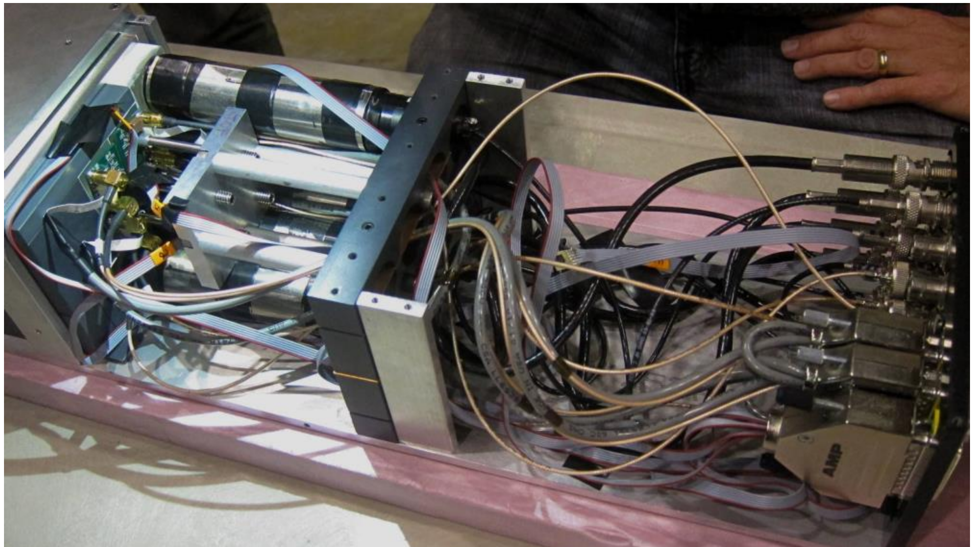
dried air
nozzle to SiPMs
45 CFPH, 0 deg C

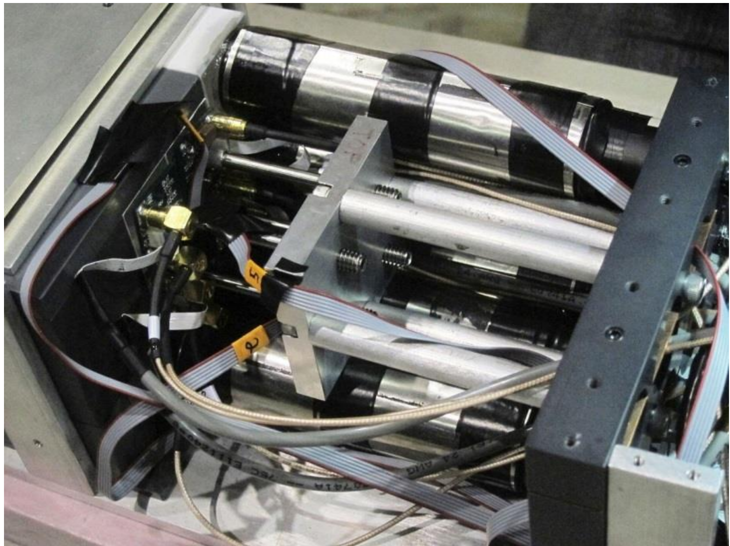


Temperature sensor

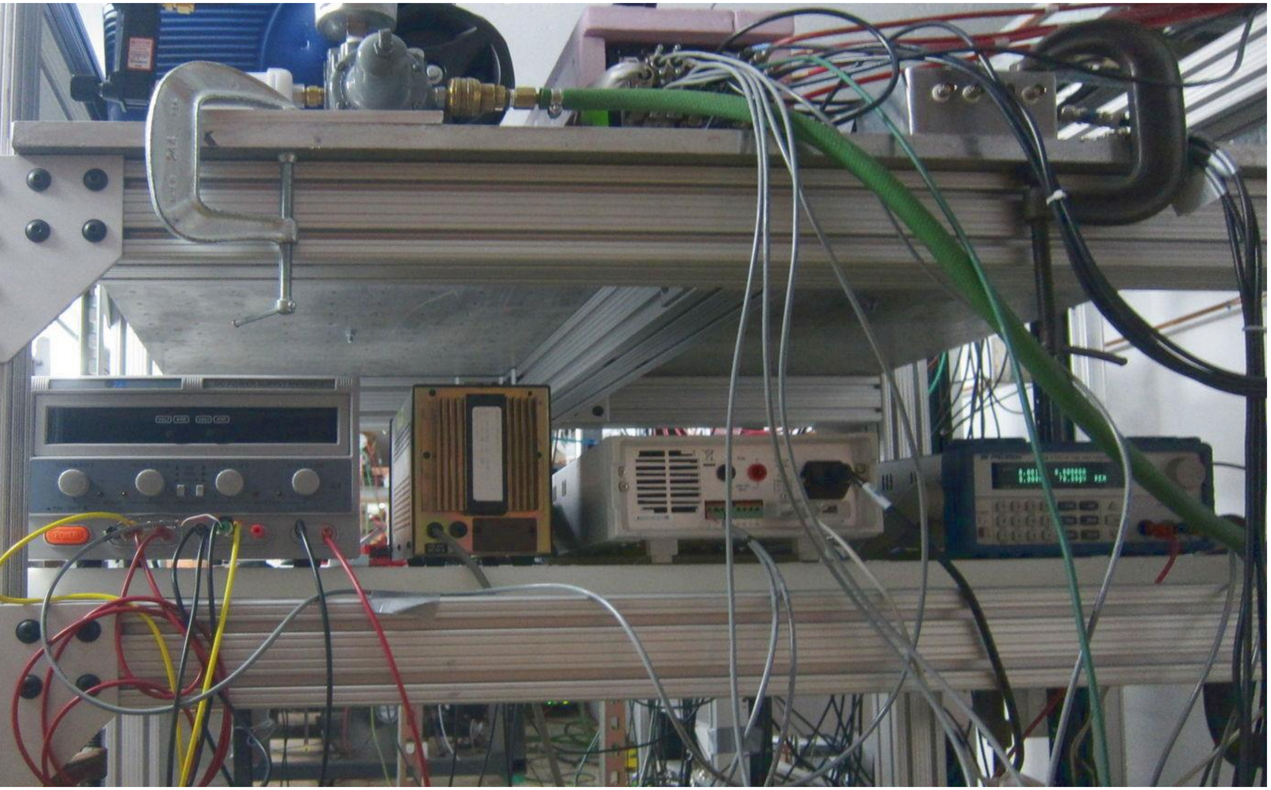
ADT7420
0.25 deg C accurate
0.0078 deg C resolution
3x3 mm, I2C (LabJack)
(batteries included)
5 inside,1 ambient



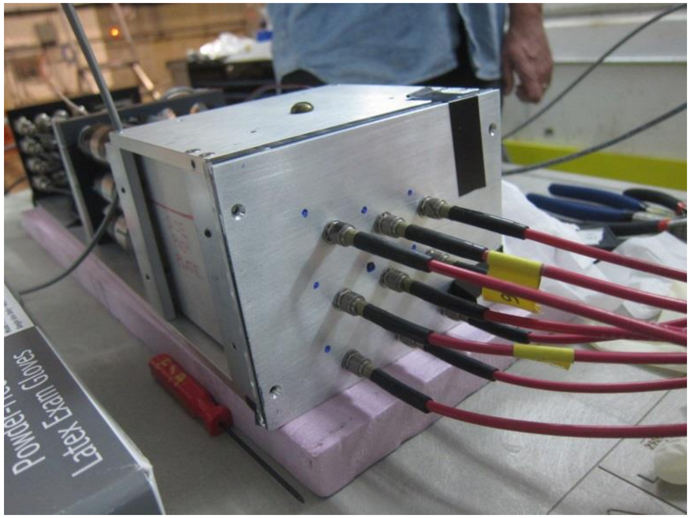




Bias control

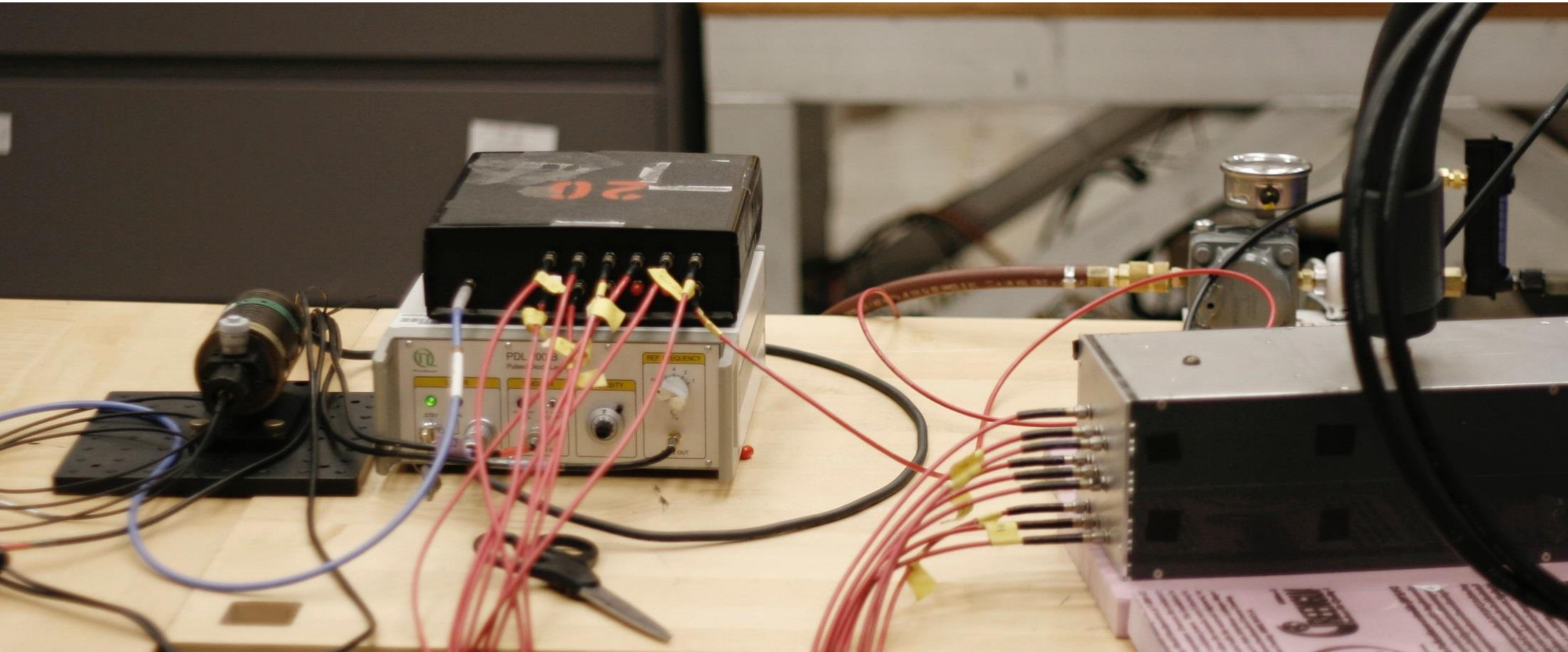


BK precision 9124
0—73 V
1 mV step
floating on 5 V
USB controlled



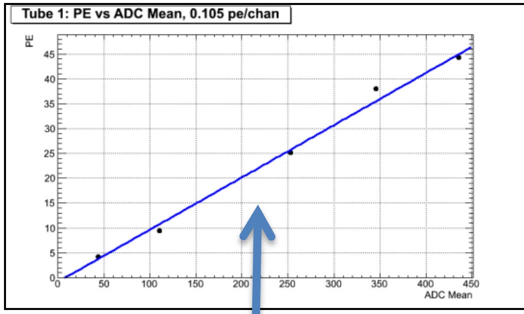
Laser Calibration

number of photons equivalent to 0.5 — 4.0 GeV



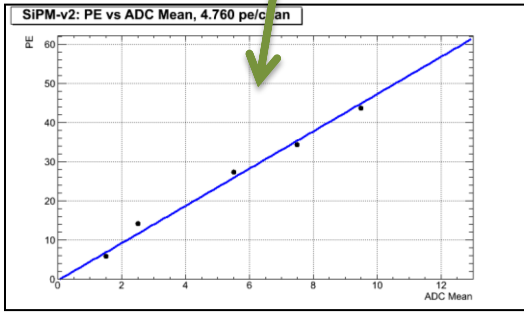
Using the mean and standard deviation of distribution

- Assume all variance comes from Gaussian photostatistics
- Relation: $$\mu = \sigma^2 \Rightarrow \sigma_{mean} = \sqrt{\frac{\mu}{N}}$$
- Calibrate as a linear fit of
$$\mu \ vs. \ \frac{\mu^2}{\sigma_\mu^2} (= N_{pe})$$
- Gives a lower limit since not all noise is photostatistics



Worked well for PMT

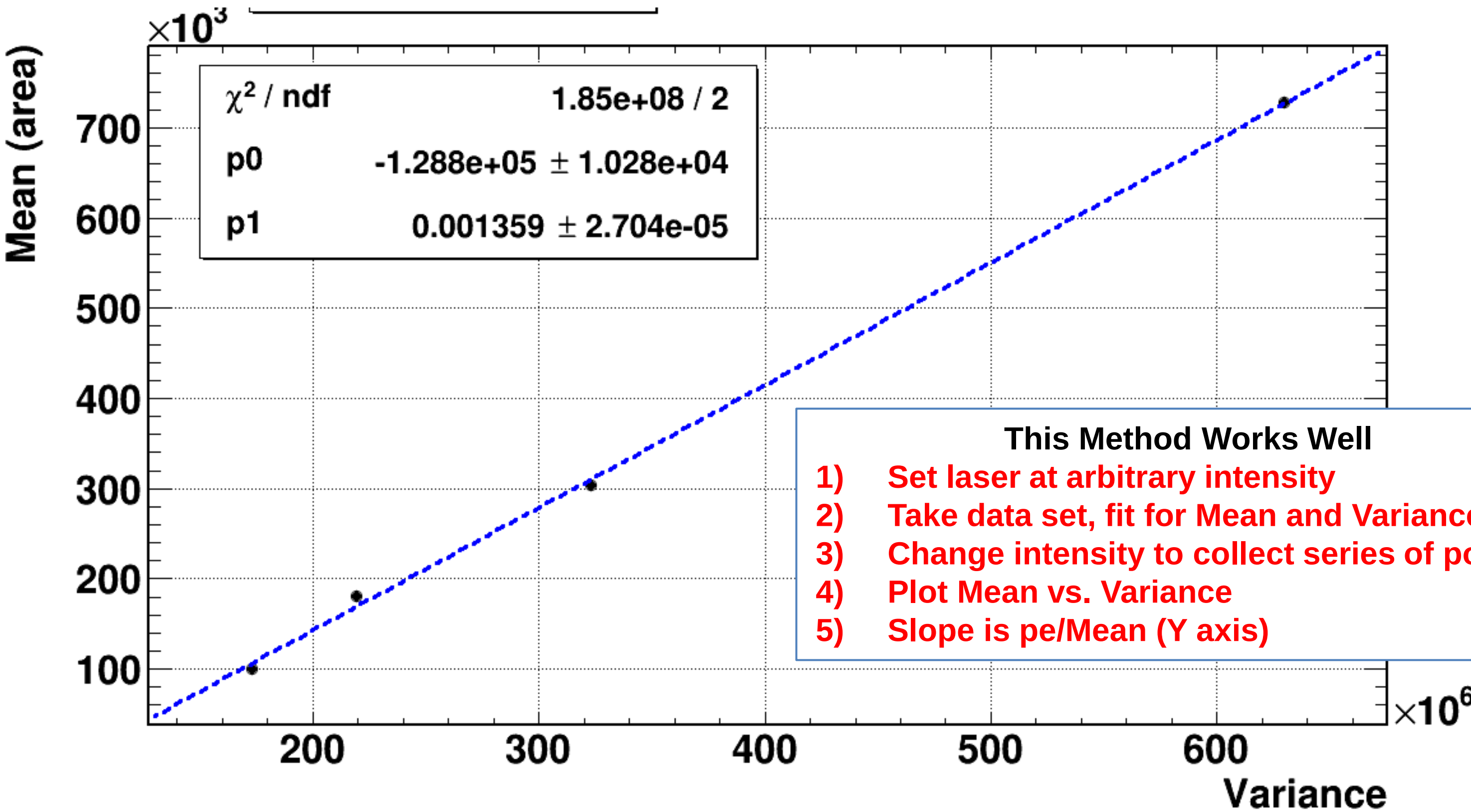
Has been trickier for SiPM (a good one)



Calibrating the Gain in terms of Fired Pixels vs pulse amplitude (or area)

$$N_{pe} = \frac{M^2}{\sigma_{pe}^2} \quad \Rightarrow \quad aM = \frac{M^2}{\sigma_{obs}^2 - \sigma_{noise}^2} \quad \Rightarrow \quad a\left(\sigma_{obs}^2 - \sigma_{noise}^2\right) = M$$

slope



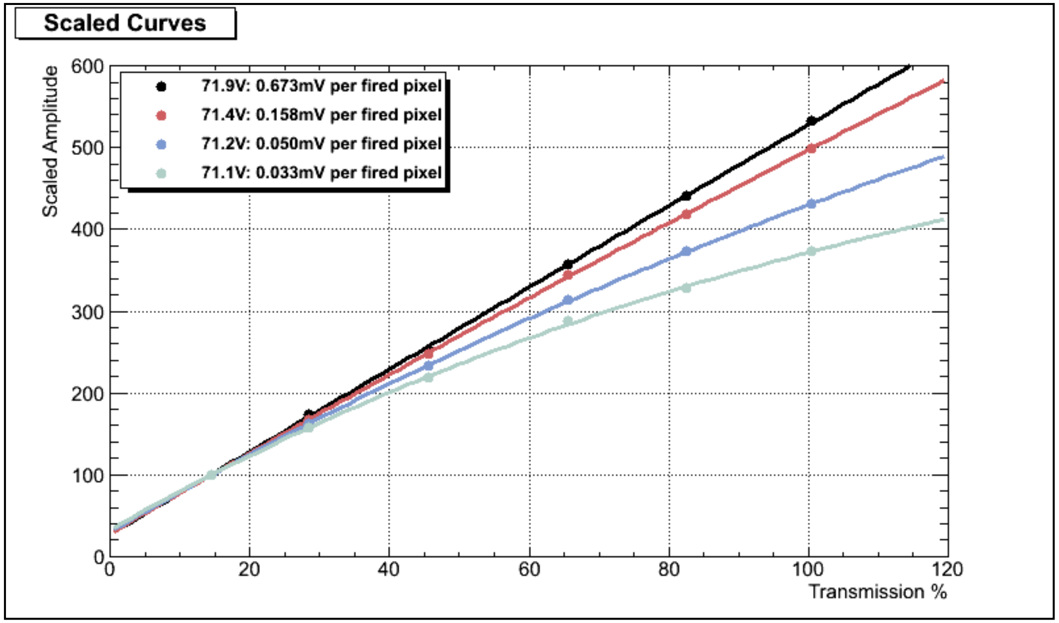
This Method Works Well

1) Set laser at arbitrary intensity
2) Take data set, fit for Mean and Variance
3) Change intensity to collect series of point
4) Plot Mean vs. Variance
5) Slope is pe/Mean (Y axis)

Note: In principle, one can also use the pixel saturation of the SiPM

- As $N_{pe} \rightarrow N_{pixels}$, the probability of multiple photons hitting a single pixel is non-negligible
- The relation is given by:

$$N_{pixels,fired} = N_{pixels}\left(1 - \exp(-N_{pe}/N_{pixels})\right)$$



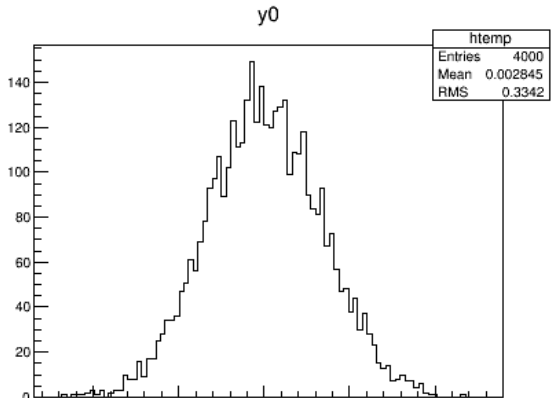
<u>SiPM from UW Lab</u>

- Adjusted laser $N_{photons}$ with optical neutral density filters
- Each line at different gain (voltage)

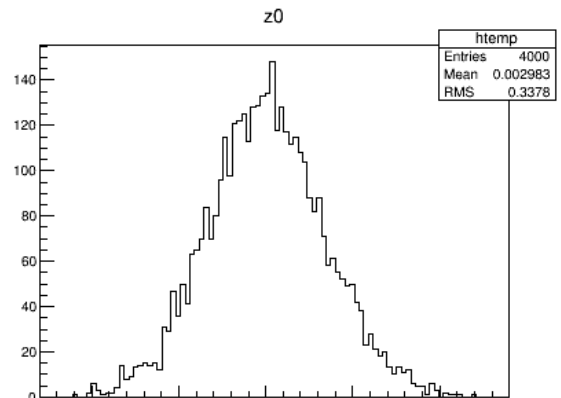
SLAC beam

Beam exiting vacuum chamber is small

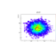
Beam hitting detector (Al windows, 6 m air) grows

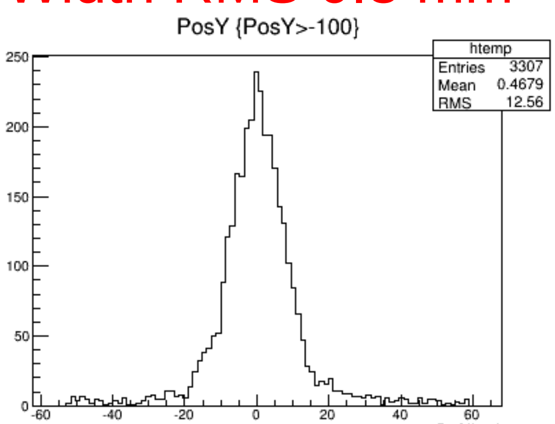


Width RMS 0.3 mm

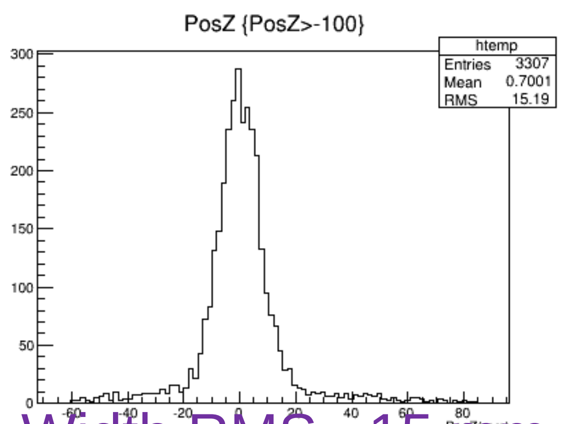


Width RMS 0.3 mm

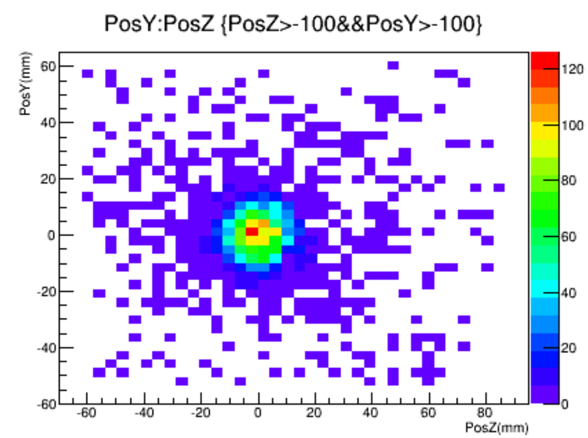




Width RMS ~12 mm

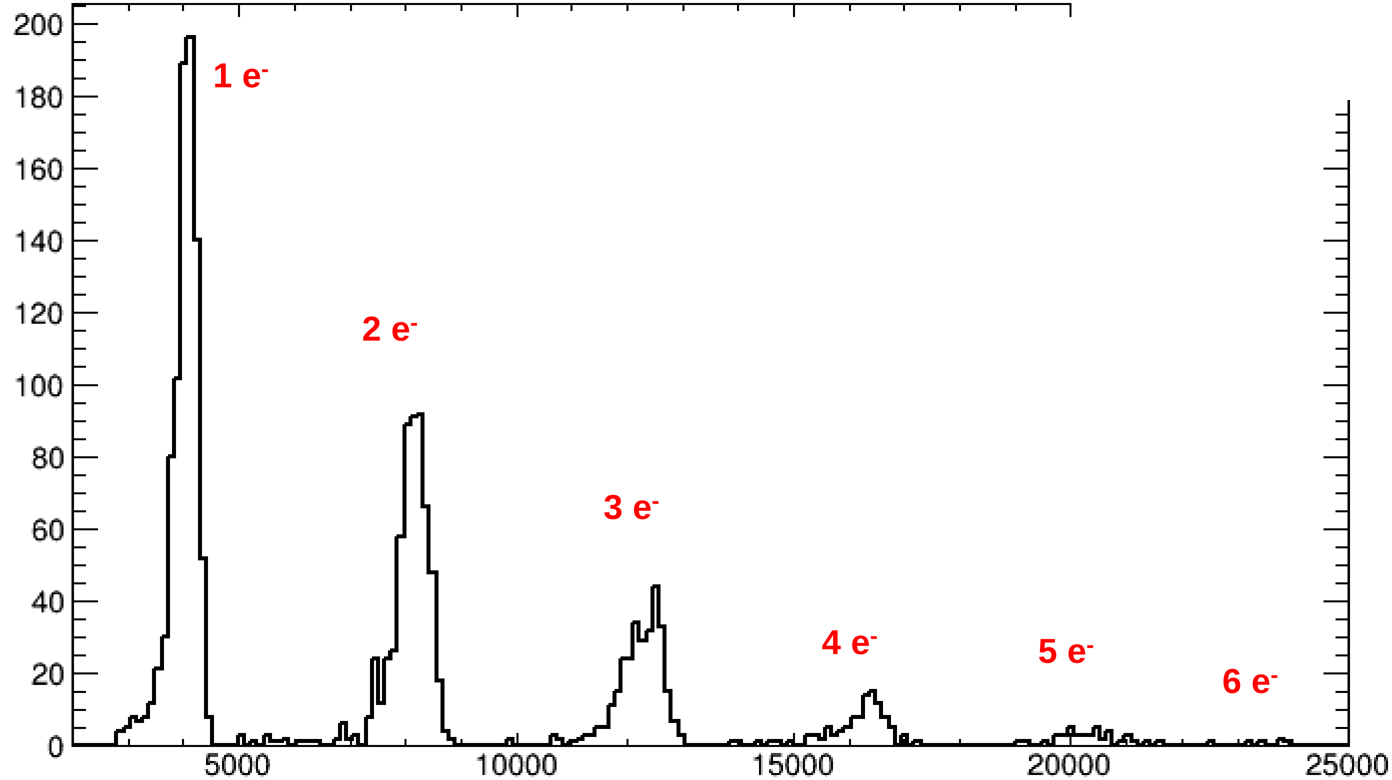


Width RMS ~15 mm



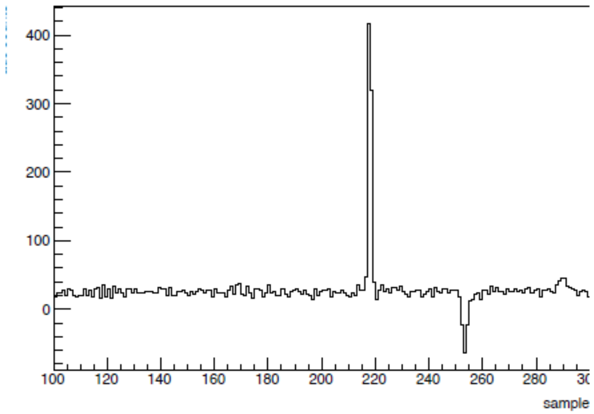
SLAC beam

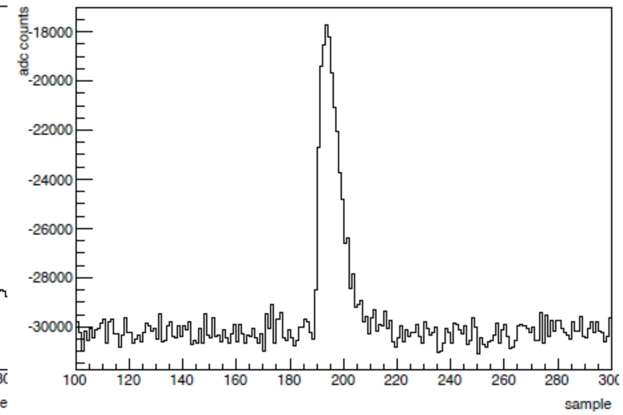
single particle Poisson distribution
2.5, 3, 3.5, 4 GeV



Intrinsic Pulses

pole zero correction, laser shot, 2 GeV, ~2000 pe

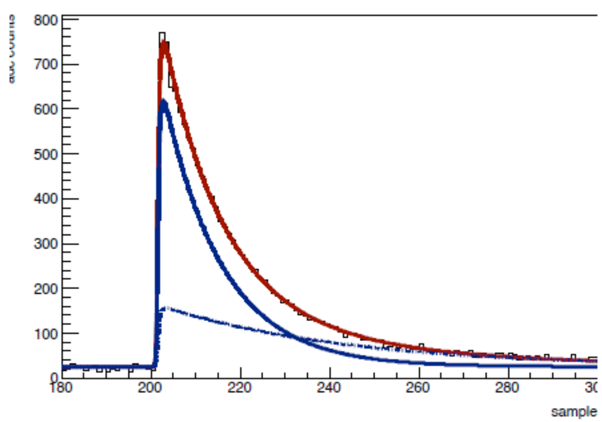


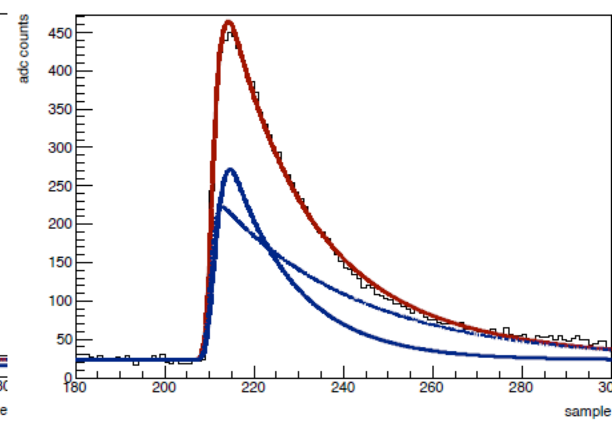


Struck

DRS: ~2 nsec FWHM

No pole zero correction, 2 GeV, ~2000 pe

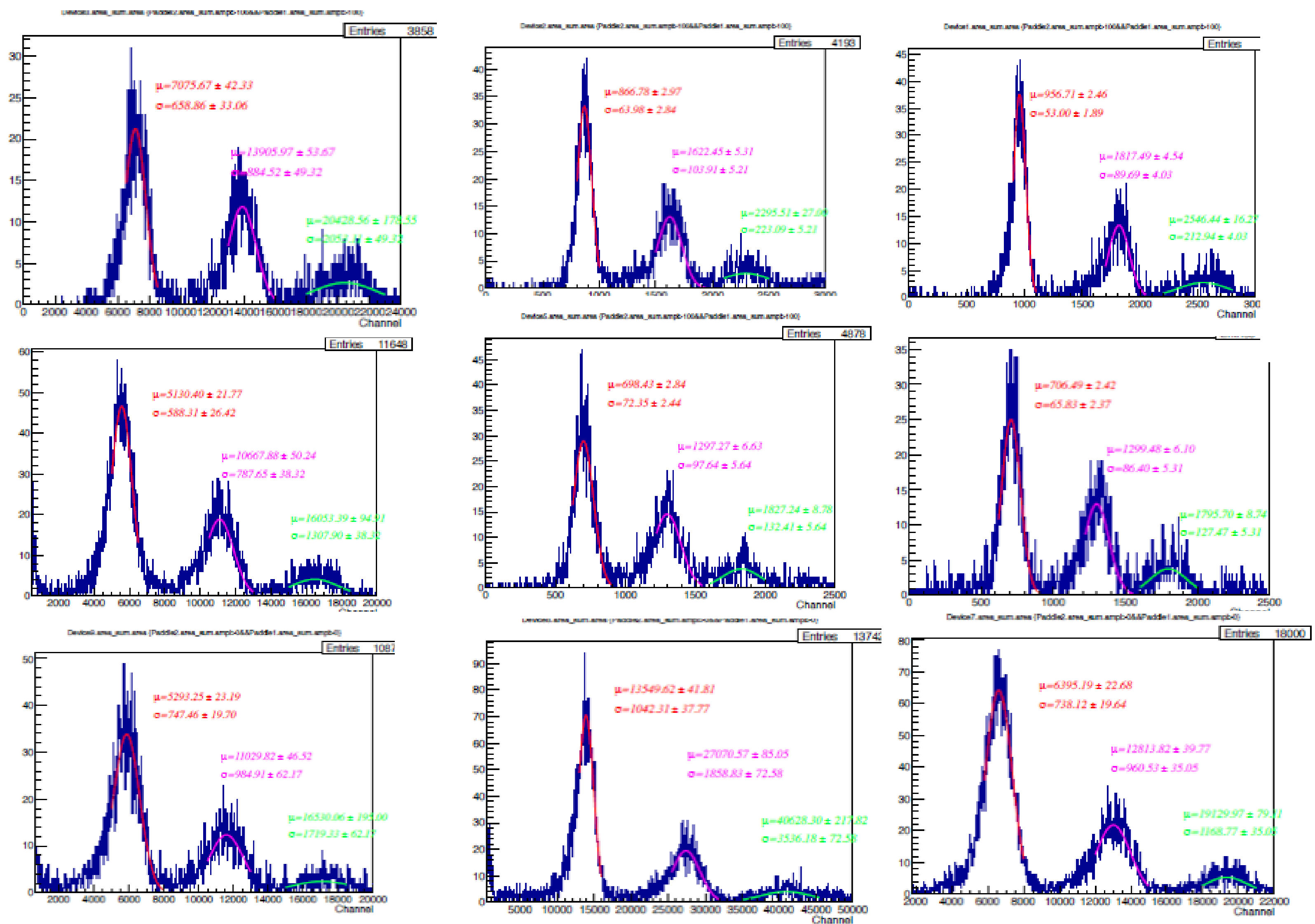




laser

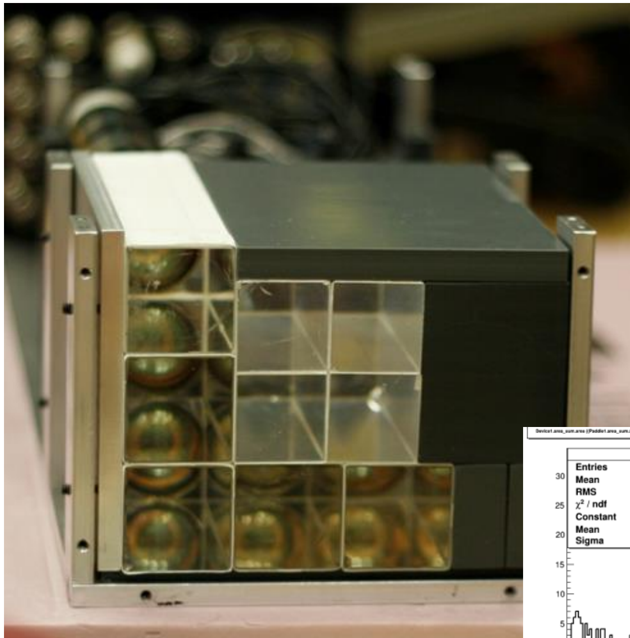
beam: ~7 nsec wider

First light

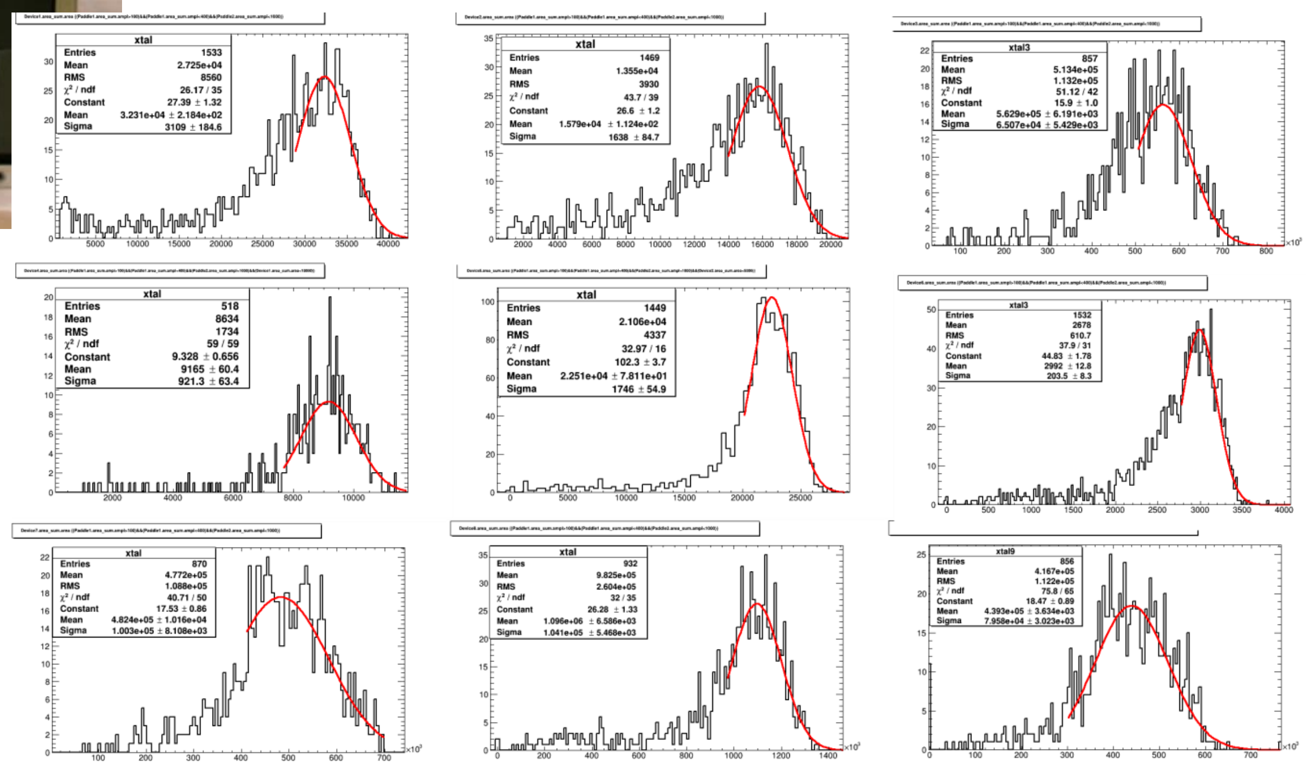


Entries 3858
μ=7075.67 ± 42.33
σ=658.86 ± 33.06
μ=13905.97 ± 53.67
μ=20428.56 ± 178.55
Channel
Entries 4193
μ=866.78 ± 2.97
σ=63.98 ± 2.84
μ=1622.45 ± 5.31
σ=103.91 ± 5.21
Entries
μ=956.71 ± 2.46
σ=53.00 ± 1.89
μ=1817.49 ± 4.54
σ=89.69 ± 4.03
σ=212.94 ± 4.03
Channel
Entries 11648
μ=5130.40 ± 21.77
σ=588.31 ± 26.42
μ=10667.88 ± 50.24
σ=787.65 ± 38.32
μ=16053.39 ± 94.91
σ=1307.90 ± 38.32
Entries 4878
μ=698.43 ± 2.84
σ=72.35 ± 2.44
μ=1297.27 ± 6.63
σ=97.64 ± 5.64
μ=1827.24 ± 8.78
σ=132.41 ± 5.64
Channel
μ=706.49 ± 2.42
σ=65.83 ± 2.37
μ=1299.48 ± 6.10
σ=86.40 ± 5.31
μ=1795.70 ± 8.74
σ=127.47 ± 5.31
μ=5293.25 ± 23.19
σ=747.46 ± 19.70
μ=11029.82 ± 46.52
σ=984.91 ± 62.17
σ=1719.33 ± 62.17
Channel
μ=13549.62 ± 41.81
σ=1042.31 ± 37.77
μ=27070.57 ± 85.05
σ=1858.83 ± 72.58
σ=3536.18 ± 72.58
Channel
Entries 18000
μ=6395.19 ± 22.68
σ=738.12 ± 19.64
μ=12813.82 ± 39.77
σ=960.53 ± 35.05
μ=19129.97 ± 79.51
Channel

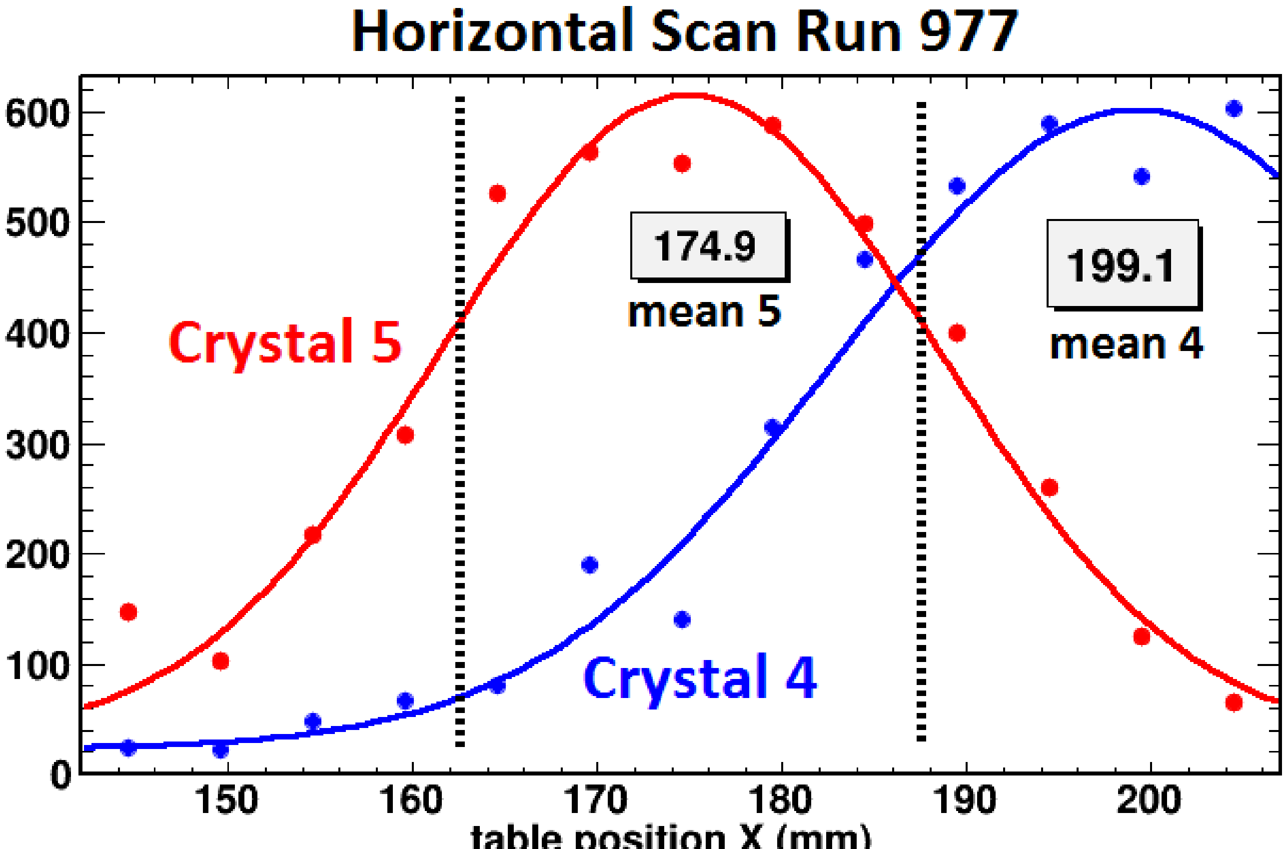
Calibrate each block one by one

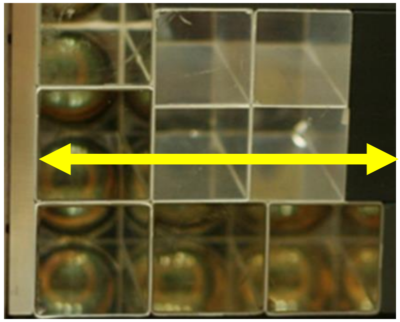


- **First find Calibration constants for each detector at their center**
- **Cut on 1 electron and avoid events that smear into other blocks**

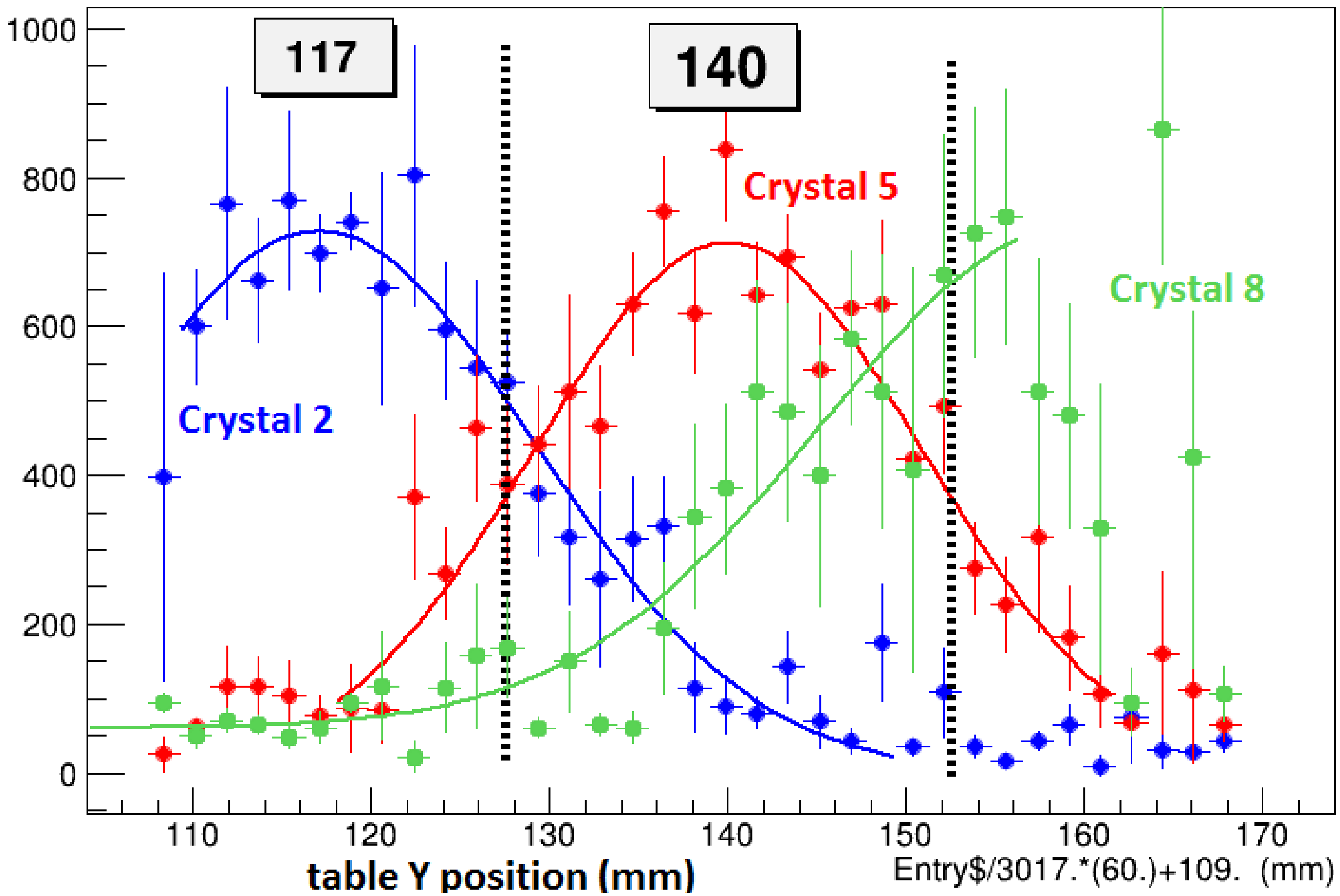


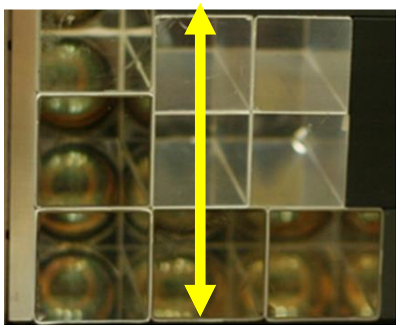
Position Scan





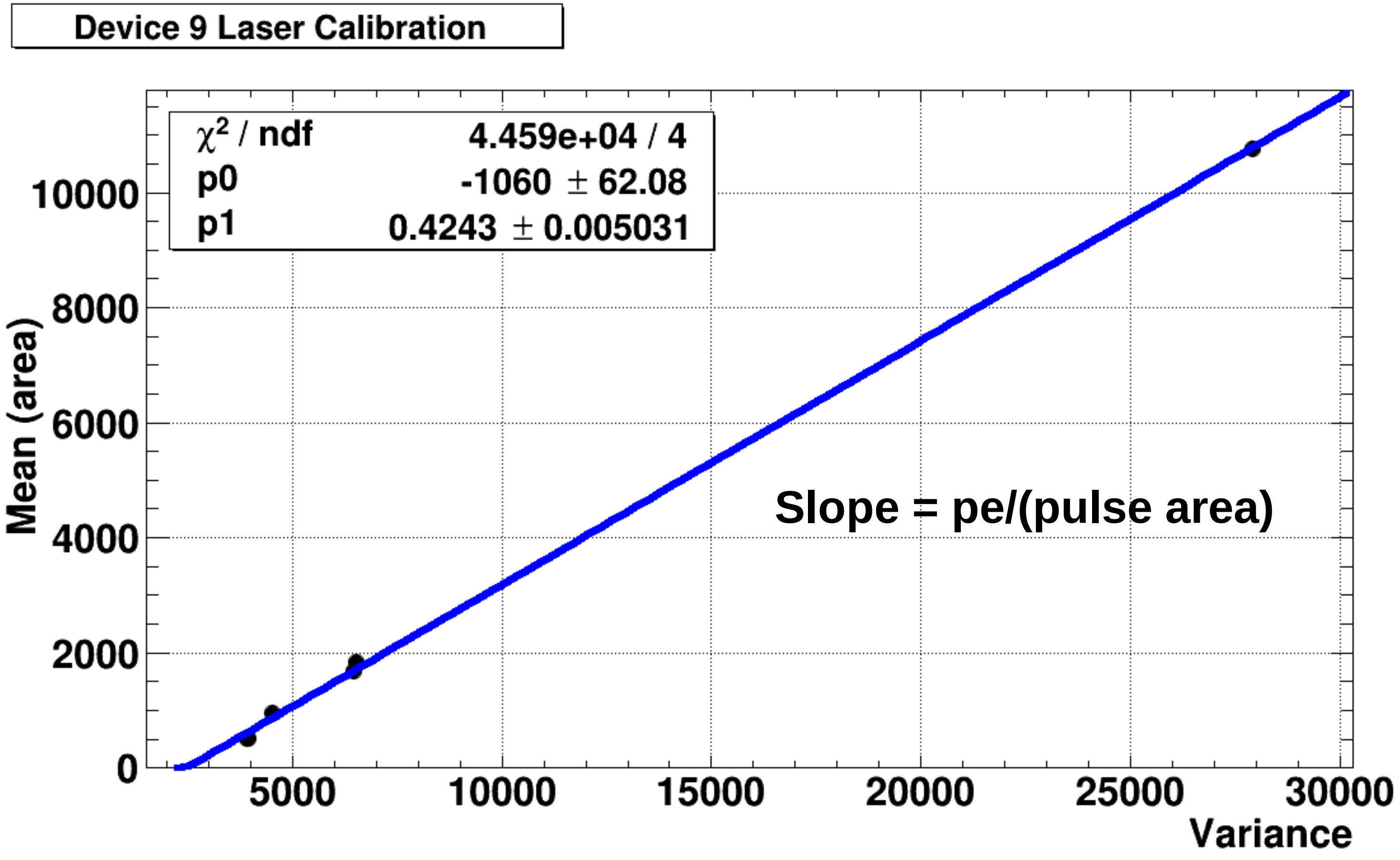
Position Scan





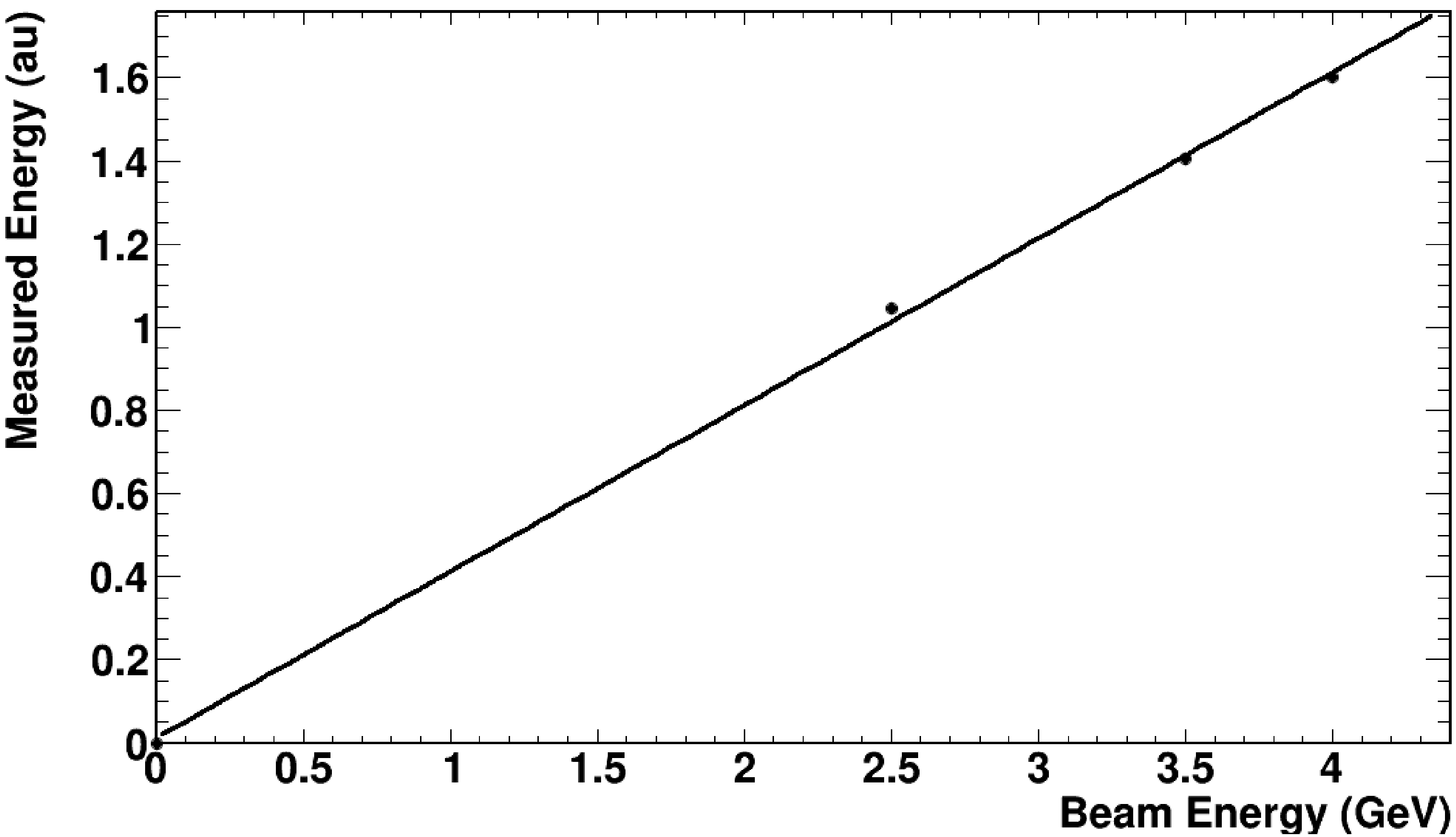
Our laser calibrations are now working well and we find the "expected" light yield from our detectors (this has been a big worry)

Corresponds to a light yield above 1000 pe/GeV (as we had hoped)

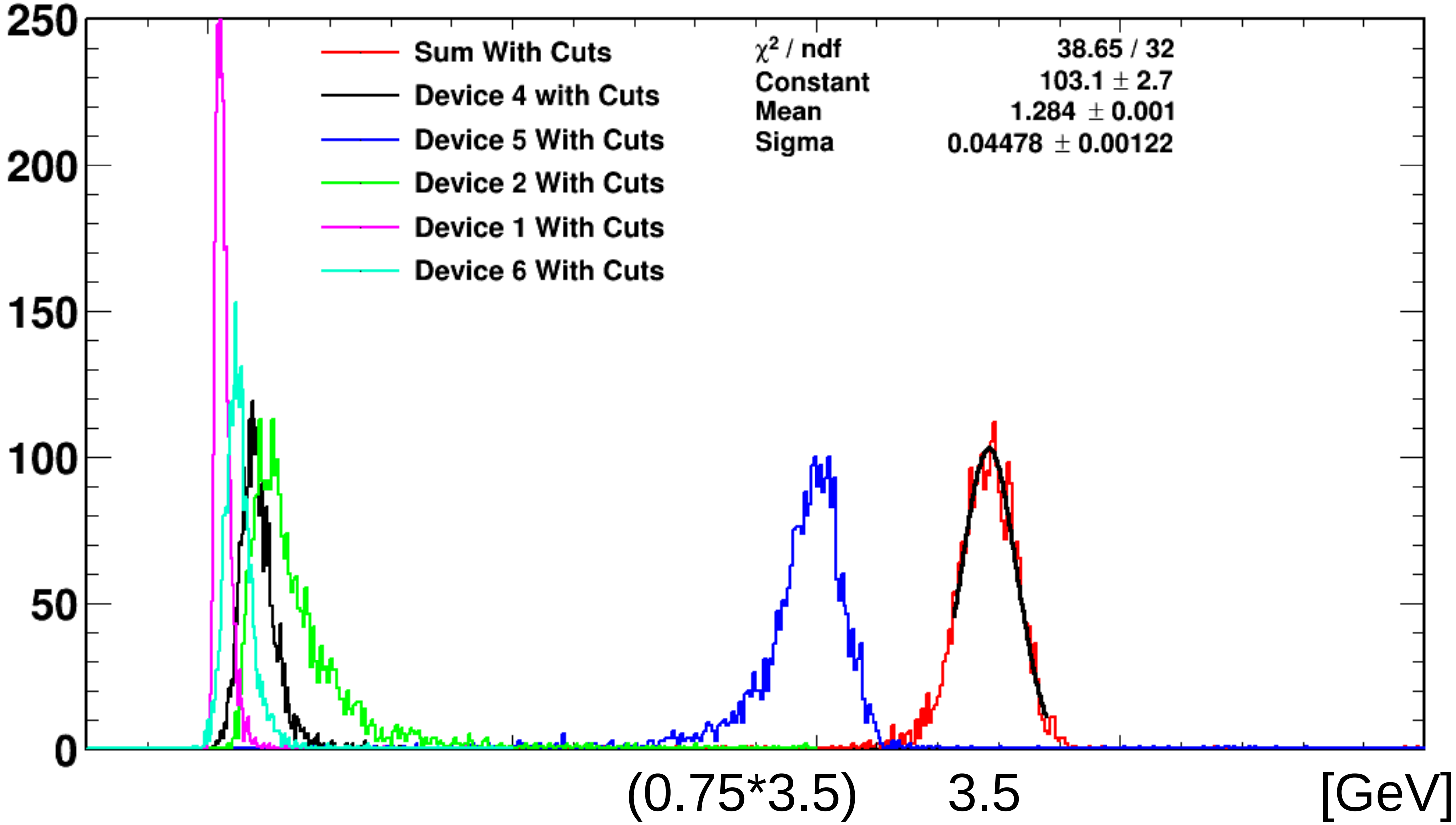


Energy Linearity

It is a calorimeter.

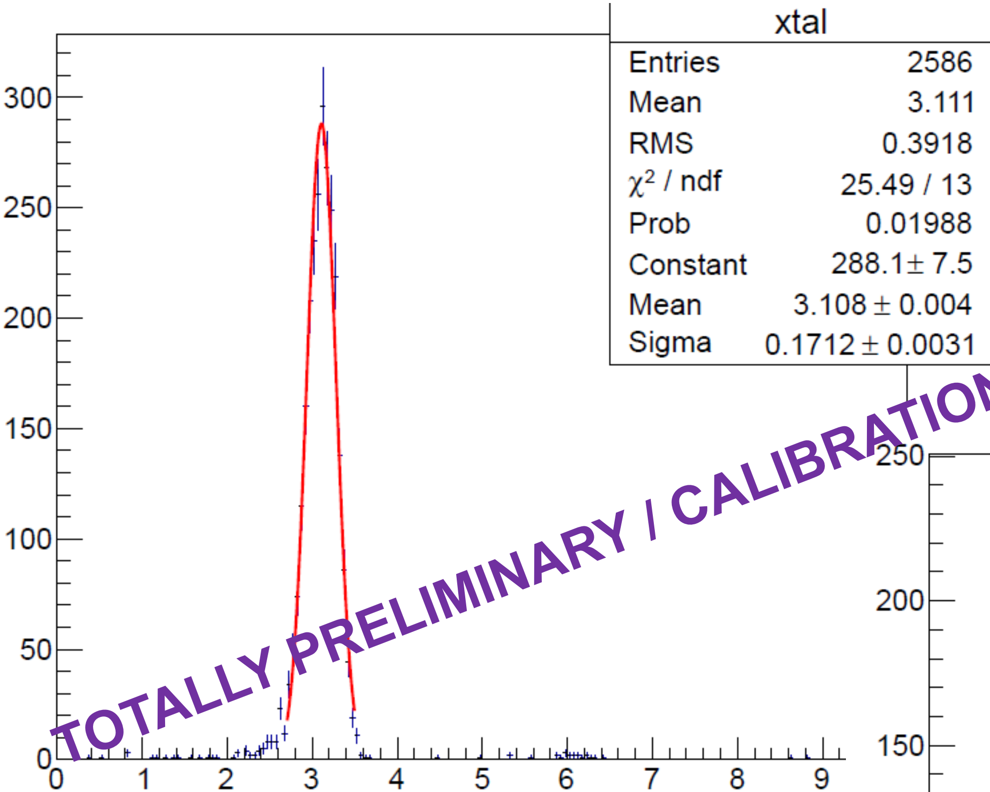


Energy sum for array



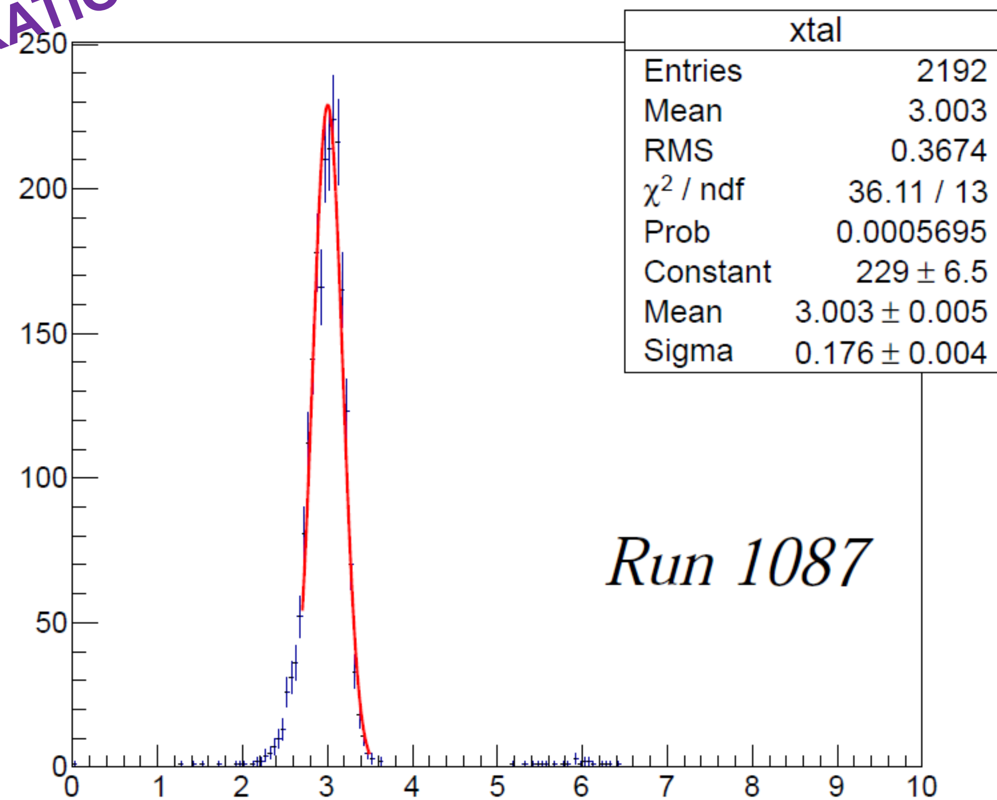
Grand sum, using combination of Monte Carlo study of shower containment and calibration constants

TOTALLY PRELIMINARY / CALIBRATION CONSTANTS NOT TUNED



Centered on the array

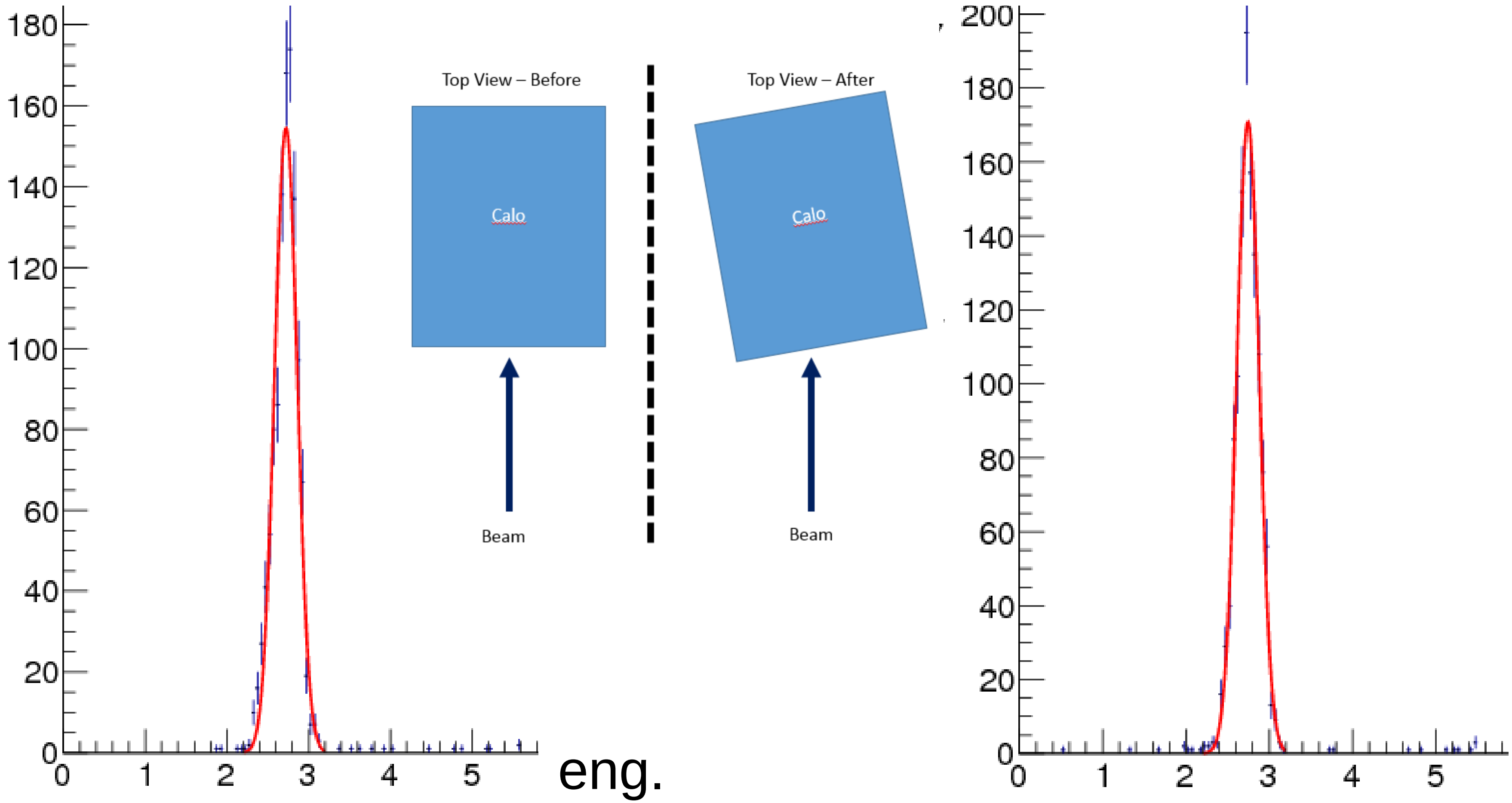
On a crack between blocks



Runs at 10 deg.

center of crystal

crack between crystals



Conclusions

PbF2 works as calorimeter

Good energy resolution

(Good timing resolution)

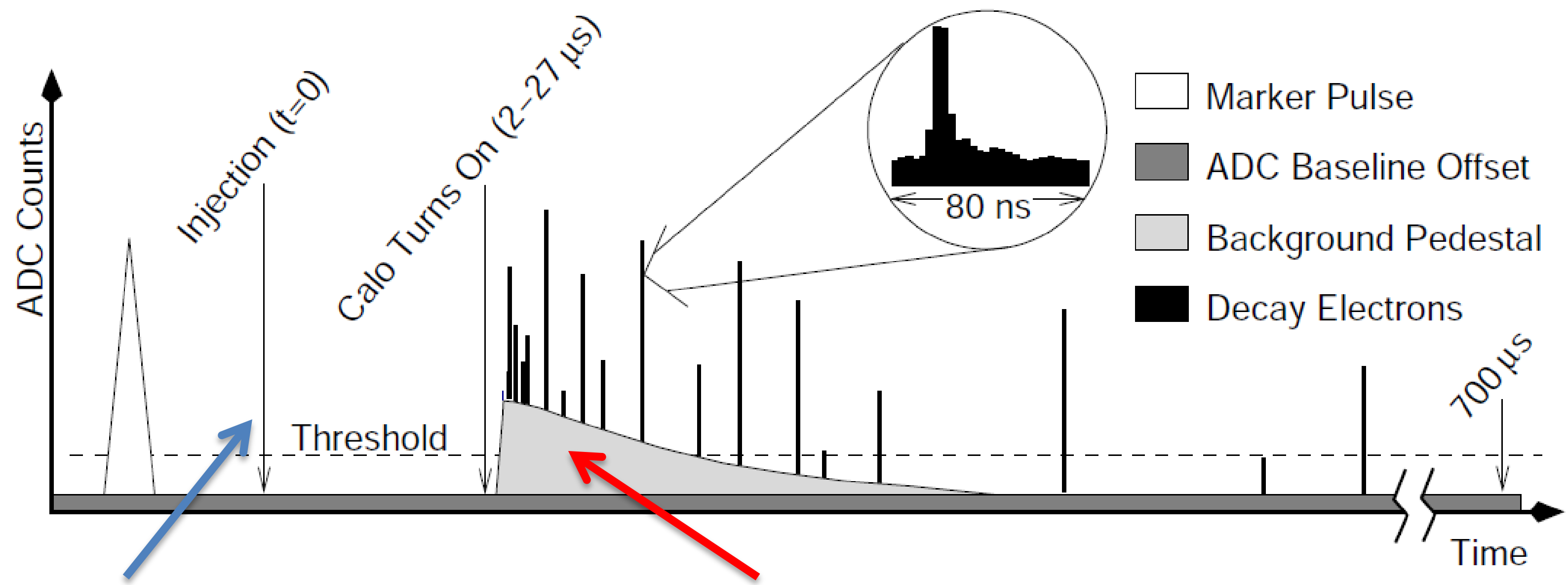
SiPMs work for readout

Summary

- **High-intensity experiments** have complex implications on detector design
  - Optimization is multi-faceted
- **PbF2** Cherenkov crystals are fast and dense
- **SiPMs** are wave of future
  - Can live in high magnetic fields
  - Are quite cost effective compared to PMTs
  - But have lots of growing pains to resolve
- **Situation evolving fast**

Prompt Flash Studies

E821 Delayed Flash Shifted Baseline during Fill
Prompt Flash was avoided by blanking off PMT gains



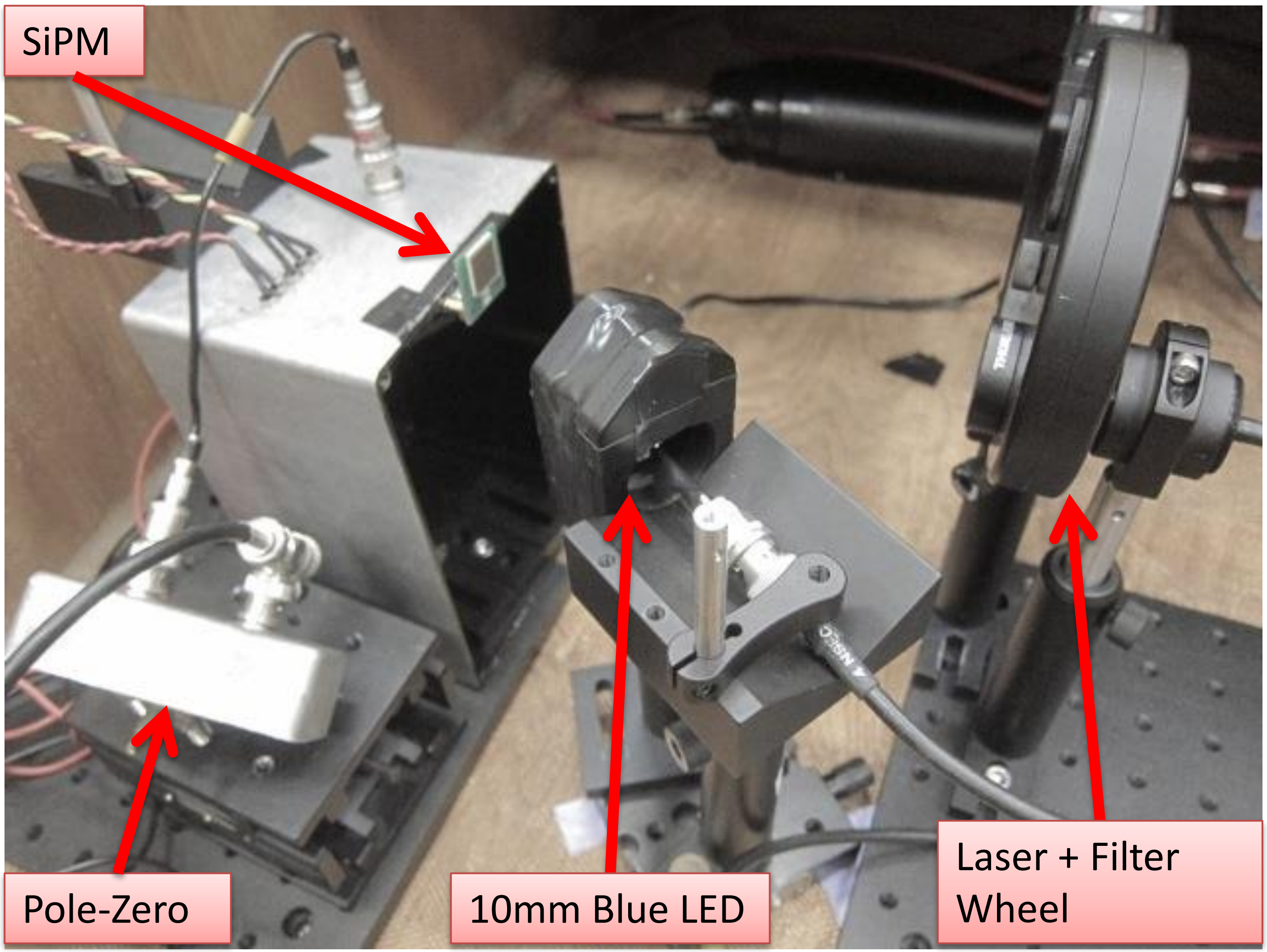
Gating for 5 to 15 μs; Recovery in 1 μs

Baseline shift caused by thermal neutron capture in scintillating fibers

<u>Question</u>: Can we survive the Prompt Flash without blanking circuits?

Estimate: 90% of ~50,000 m+ don't store → If 10% hit some unlucky crystal, that will more than saturate all pixels of the SiPM. How fast can we recover?

Setup: Prompt Flash→ LED
Decay Positron → Laser



Logic: Compare laser with and without preceding LED “FLASH”

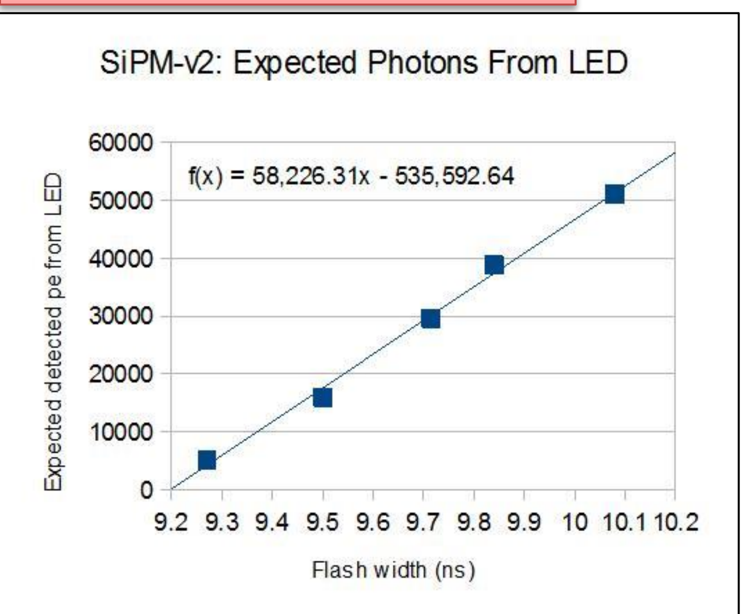
Event Trigger ≈100Hz

Gate Delay Generator

Laser Trigger

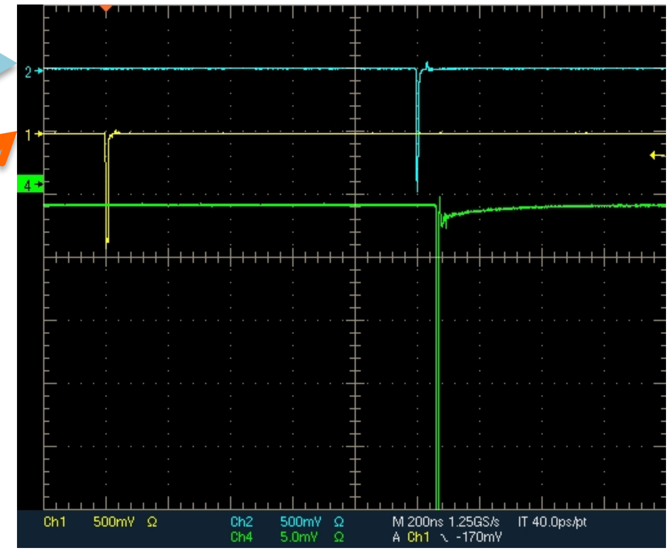
LED Trigger

Adjust trigger width for size of flash in pixels

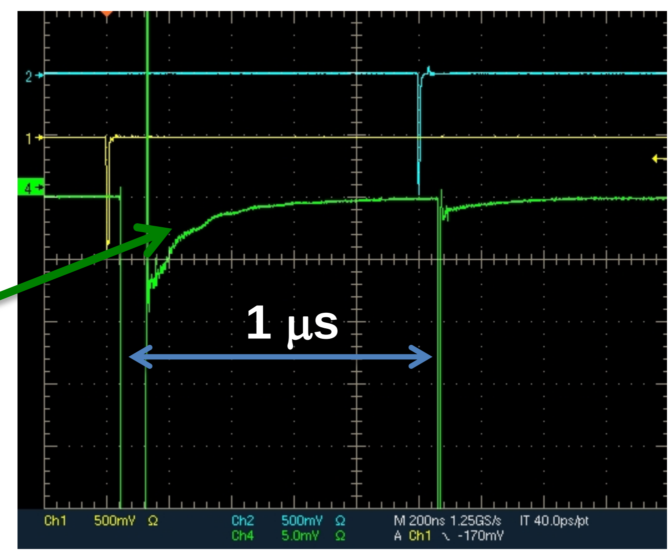


Delay controls timing between LED and Laser ≈ 1 μs at right

Only Laser

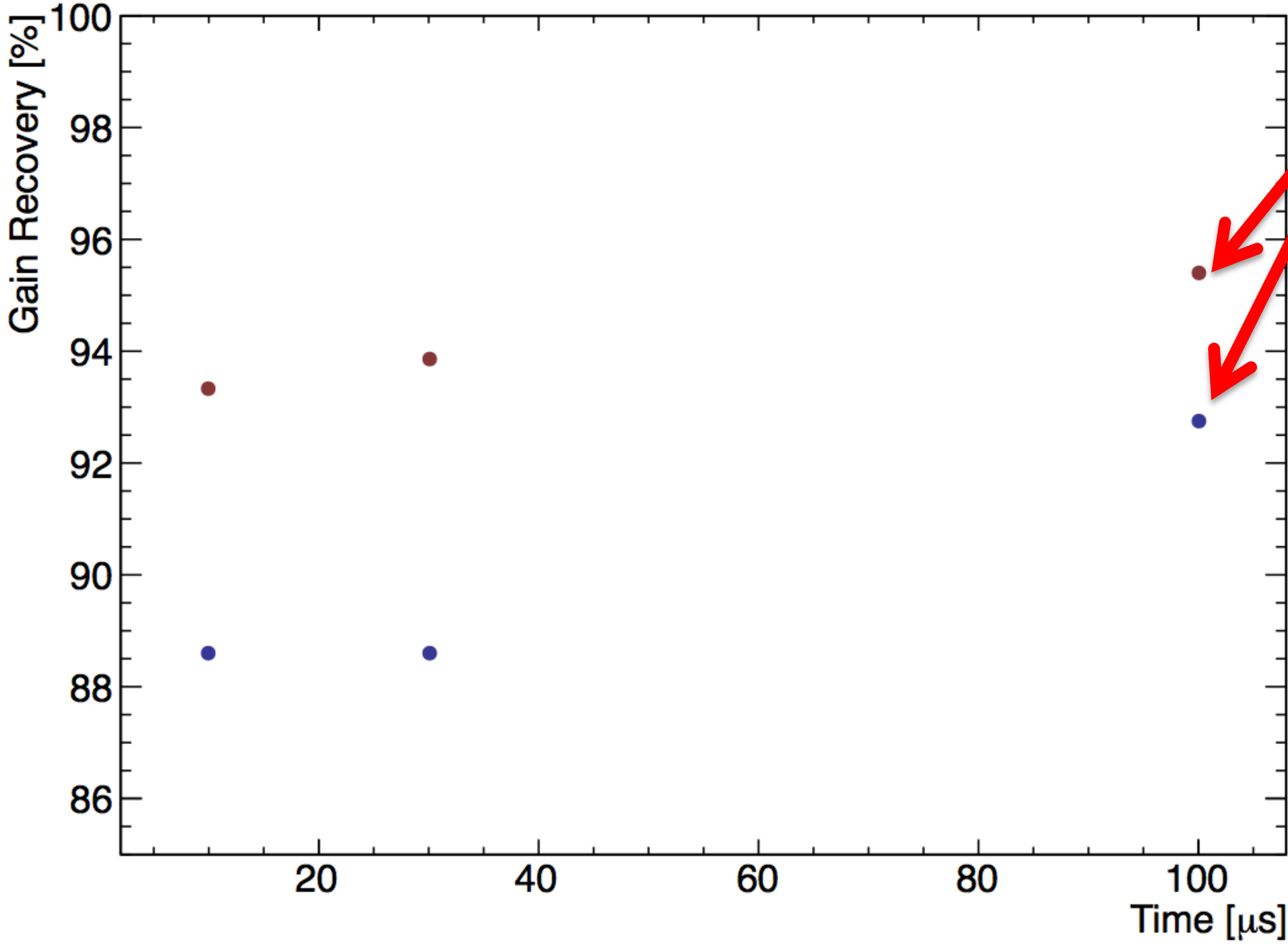


LED + Laser



SiPM Response

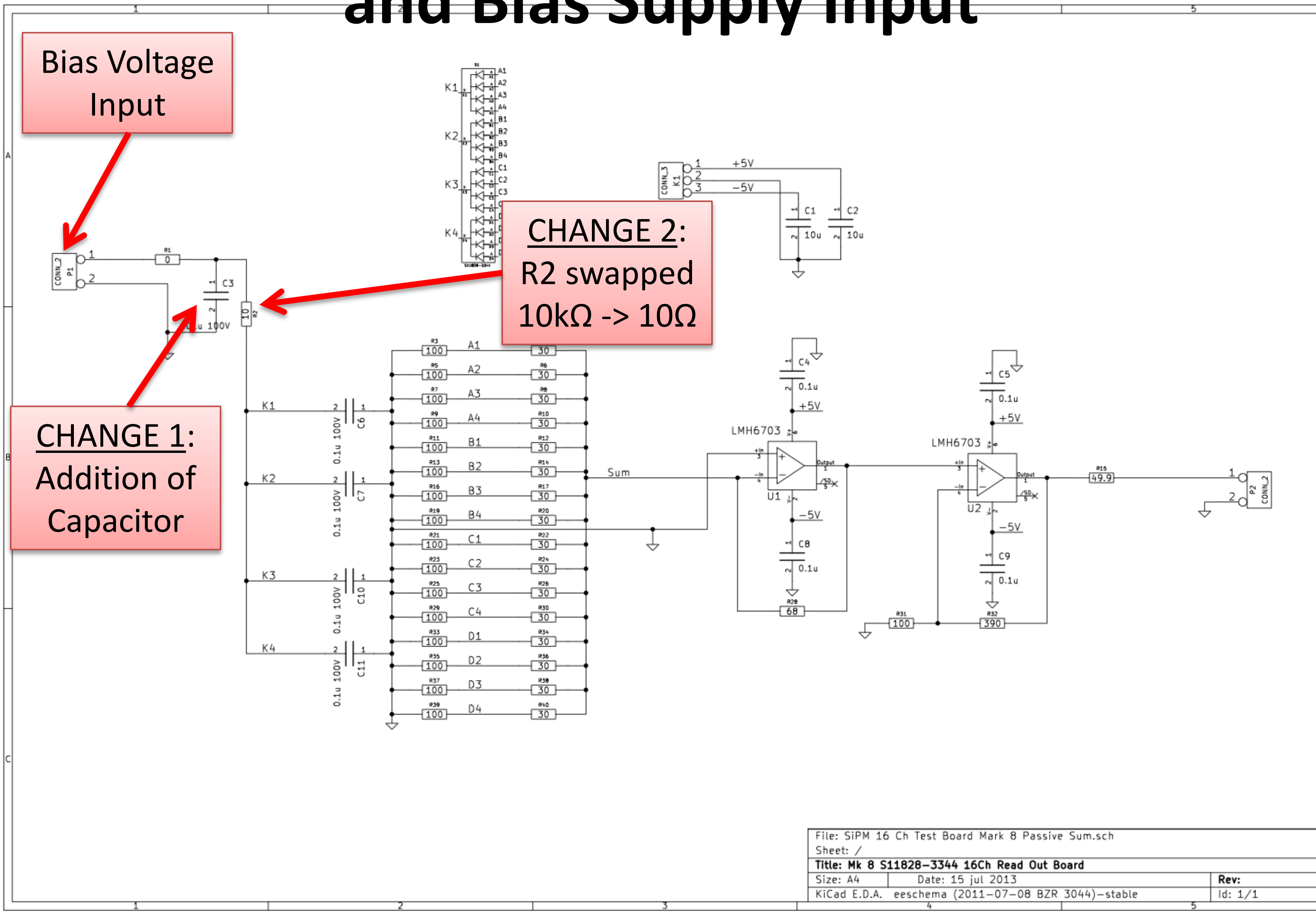
First attempt: Miserable failure (ugh)



Unacceptable gain sag **at 100 μs**

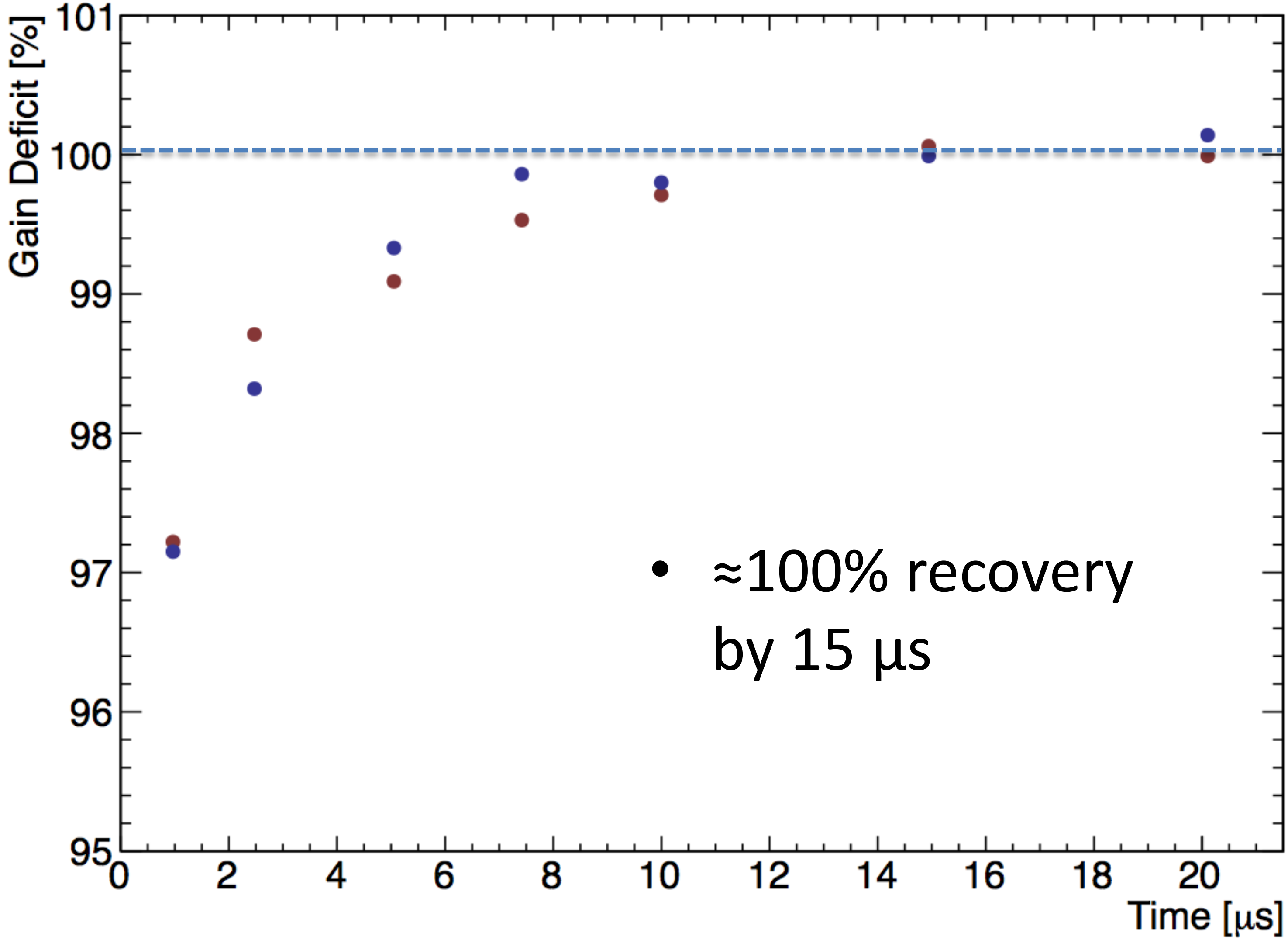
Red and **Blue** are two different devices with same SiPM board

Modifications to SiPM Board Schematic and Bias Supply Input



Current Results are Promising

(will be repeated for next generation boards)



Electronics

NIM trigger logic

> trigger on beam or “on light”

> scint. paddles online

> beam finder offline (SiPM/scint)

> remote switch/delay control

SiPMs

> pole zero network (opt)

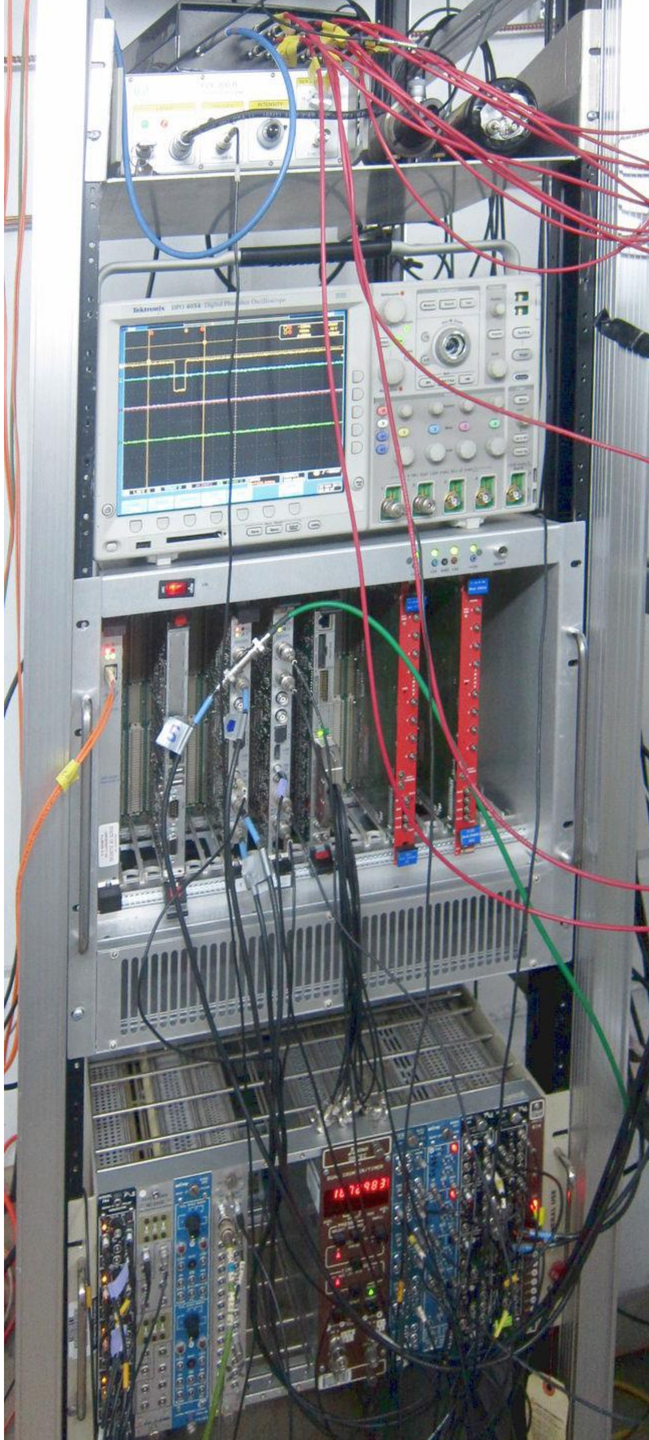
PMTs

> T-bridge (impedance match, opt)

Digitizers

> SiPMs, PMTs

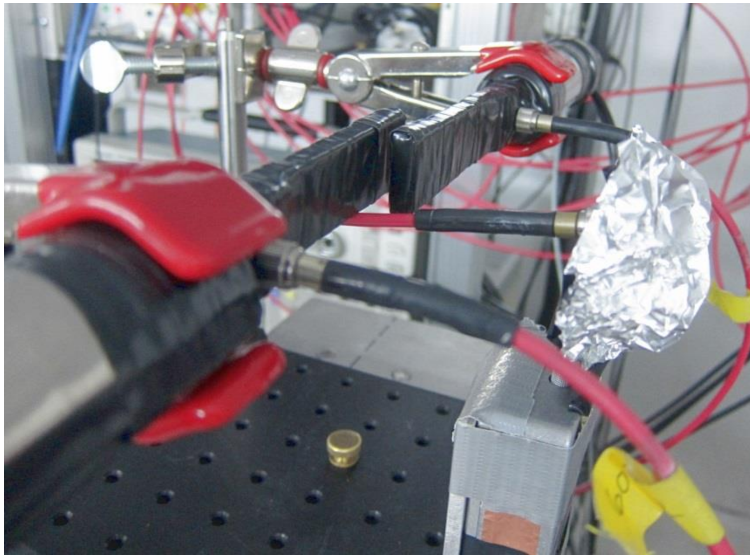
> scint. paddles, beam finders

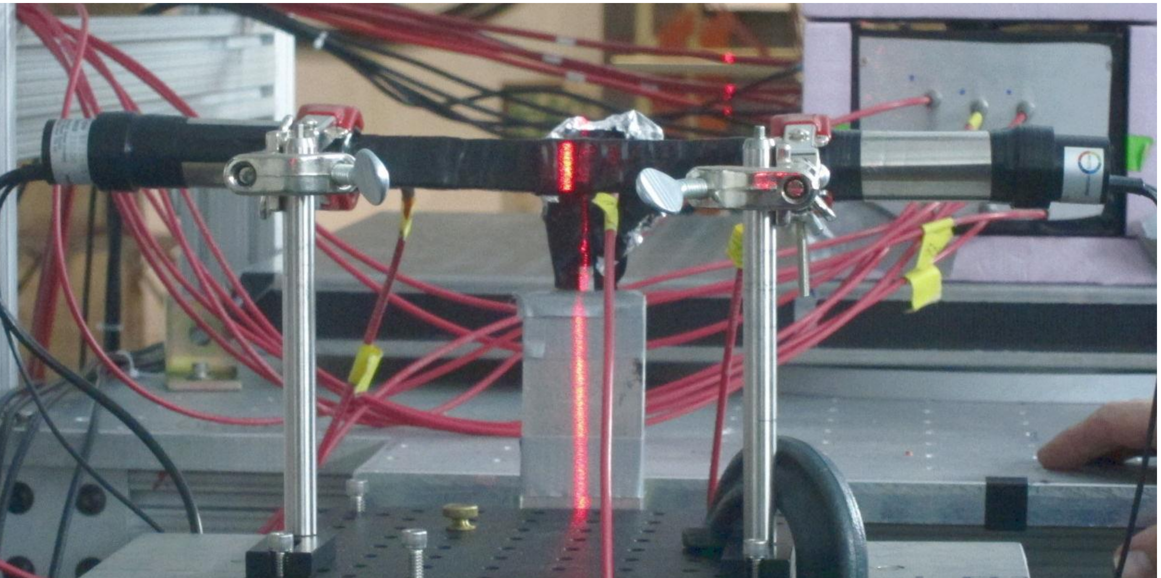


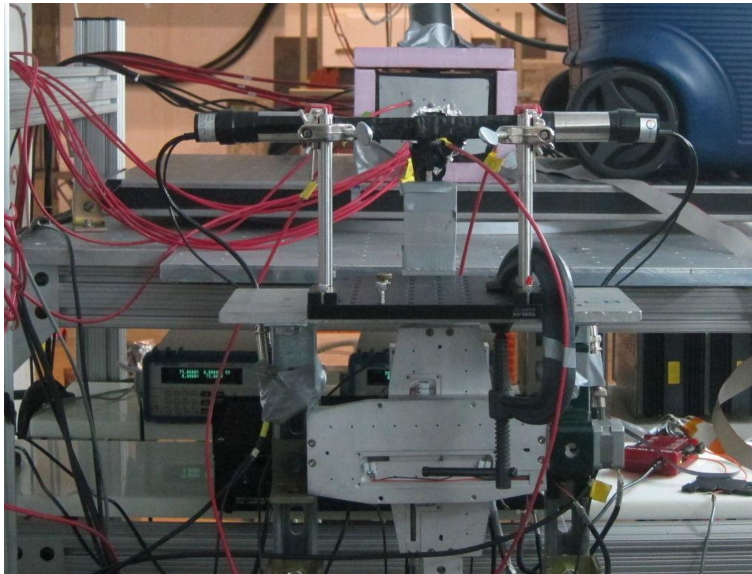
Scintillator paddles

2 paddles in coincidence
trigger “on light”
data quality flag

moveable beam finder (remote)







Digitizers

Struck SIS 3350

> Pipelined Flash ADC
> 500 MSps, 12 bit, 4 ch

PSI DRS4

> Capacitor Array (1024, 5GHz, 8ch)
> then ADC (33 MSps, 16bit)

Light Yield

1.0 pe/MeV